Methodology for Sizing Finished Goods Inventories for a Vinyl Siding Extrusion Plant

by

Michael Gary Milby

B.S., Mechanical Engineering, Brigham Young University, 1991

Submitted to the Sloan School of Management and the
Department of Mechanical Engineering
In Partial Fulfillment of the Requirements for the Degrees of

Master of Science in Business
and
Master of Science in Mechanical Engineering

In Conjunction with the
Leaders for Manufacturing Program

at the
Massachusetts Institute of Technology
May 1999
[June 1999]

Signature of Author ______________________________
Sloan School of Management
Department of Mechanical Engineering
May 7, 1999

Certified by ______________________________
Professor Stephen C. Graves
Sloan School of Management

Certified by ______________________________
Dr. Deborah J. Nightingale
Department of Aeronautics and Astronautics

Accepted by ______________________________
Larry Abeln, Director of Master's Program
Sloan School of Management

Accepted by ______________________________
Professor Ain Sonin, Chairman, Graduate Committee
Department of Mechanical Engineering

Read by ______________________________
Professor David Cochran
Department of Mechanical Engineering

This page intentionally left blank.

Methodology for Sizing Finished Goods Inventories for a Vinyl Siding Extrusion Plant

by
Michael Gary Milby

Submitted to the Sloan School of Management and
the Department of Mechanical Engineering, on May 7, 1999
in Partial Fulfillment of the Requirements for the Degrees of
Master of Science in Business and
Master of Science in Mechanical Engineering

Abstract

Recently, many companies have begun to implement lean manufacturing principles as a way to improve their production systems. Alcoa has joined the movement to adopt lean manufacturing, and has named their effort the Alcoa Production System (APS), after the Toyota Production System which is, doubtless, the best known example of lean manufacturing implementation.

The thrust of lean manufacturing is the removal of waste from the production system. For most companies the biggest reason for implementing lean manufacturing is that of reducing excess inventory. However, before inventory can be removed it is important that the reasons for holding inventory are understood. Only after these drivers of inventory are improved or removed, can companies safely reduce their inventories without losing their ability to satisfy customer demand.

If implemented correctly, lean manufacturing is a great way to systematically reduce waste, especially inventory. However, most reference texts on lean manufacturing implementation have very little specific information on how much inventory is appropriate at any stage of improvement.

On the other hand, practitioners of operations management have been dealing with these issues for years, and there exists a body of knowledge on sizing inventories.

Many fail to realize that these two fields of study are compatible and that the base stock model is fully compatible with lean production methods. It is the objective of this thesis to show that the base stock model is compatible with lean manufacturing, and is an appropriate model for determining the correct levels of finished goods inventories at the Denison Alcoa plant.

Thesis Advisors: Professor Stephen C. Graves
Sloan School of Management

Dr. Deborah J. Nightingale
Department of Aeronautics and Astronautics

Reader: Professor David Cochran
Department of Mechanical Engineering

This page intentionally left blank.

Acknowledgments

The author gratefully acknowledges the support and resources made available to him through the MIT Leaders For Manufacturing program, a partnership between MIT and major U.S. manufacturing companies.

I would like to thank my wife, who sacrificed so much time and energy to help me be successful in this endeavor. She is always helpful and encouraging to me, and was almost a single parent to our two, then three, children for two years. Thank you...I love you Melanie.

I'd also like to thank my children who had to share their daddy with school for two years. I know it was a sacrifice for them as well.

I'm also thankful to my parents who taught me a good work ethic, and to the entire extended family that has been supporting and loving in my efforts to grow.

I would like to acknowledge my advisors, Steve Graves and Deborah Nightingale, for their knowledge, experience and patience with me while I was learning on my internship and through my thesis experience.

Finally, I'd like to give my thanks everyone at Alcoa that helped to make my internship a learning, and growing experience, especially...

- Craig Galloway, Jeff Jackson, Scott Jacobsmeyer, Mike McCullom, Doug Morrow, Gary Oler, Ty Scopel, Bill Seffrin, Charlie Vass, Fred Wagner, and Susan Wyatt who endured my many questions.
- Phyllis Coker who kept my overworked computer running and helped me to understand a few important things about leadership.
- Larry Adams, Mike Anderson, Charles Collins, Gale Powell, Tim Smith, Gary Stutz, and Bobby Thomas for their support of the projects that I was working on while at Alcoa.

This page intentionally left blank.

Table of Contents

List of Figures and Tables

This page intentionally left blank.

Introduction

1.1 Project Background

Recently, many companies have begun to implement lean manufacturing principles as a way to improve their production systems. Alcoa has joined the movement to adopt lean manufacturing, and has named their effort the Alcoa Production System (APS), after the Toyota Production System which is, doubtless, the best known example of lean manufacturing implementation.

Early in 1997 Alcoa Building Products (ABP), a division of Alcoa, began the long journey toward implementing lean manufacturing. I joined the effort for almost seven months starting in June of 1998 as part of the Leaders for Manufacturing Program (LFM) at Massachusetts Institute of Technology (MIT). I interned at the ABP vinyl extrusion plant in Denison, Texas with the purpose of helping with the movement to "go Lean."

The thrust of lean manufacturing is the removal of waste from the production system. For most companies the biggest reason for implementing Lean is that of reducing excess inventory. In fact, it has been my experience that many companies focus on inventory long before they understand what the mechanisms are that determine how much inventory is really needed to make the production system run smoothly. Much to the Denison Plant's credit, they realized that there were many factors that determined how much inventory was required, in order to ensure that they were able to satisfy demand. When I came to Denison, they had greatly reduced their inventory from the excessive amounts that they had held in the past, but they were at the point where they needed to understand the drivers of inventory before they could make further improvement plans.

1.2 Research/Thesis Objective

While at Denison, it was my assignment to find a method to size finished goods inventories (FGI) in order to fulfill customer demand at a given level, and to understand what constraints in the plant most greatly affected the amount of FGI required.

It is the objective of this thesis to show that the Base Stock model is compatible with lean manufacturing, and is an acceptable model for determining the appropriate levels of finished goods inventories in the Denison environment.

1.3 Thesis Structure

In Section 2 I present in more detail the situation at the Denison plant. In this section I discuss the products, the manufacturing processes, the personnel, the introduction of lean manufacturing, the plant personnel, and the problems encountered with appropriately sizing inventories.

In Section 3 I do a brief literature review of selected papers and texts pertaining to inventory policies.

Section 4 is a discussion of the history and relevance of lean manufacturing to production.

Section 5 is a more detailed look at the inventory and pull system problems at Denison.

In Section 6 I detail the process used to characterize the demand and production capabilities of the Denison plant, apply the base stock model, and to verify the applicability of the base stock model to this particular situation.

And finally, in Section 7, I discuss my conclusions and recommendations for the Denison plant and their use of inventory policy in a lean manufacturing environment.

2 Company Background

2.1 Alcoa Building Products

Alcoa is a global company with 215 operating locations, organized into 24 business units in 31 countries. Alcoa earned revenues of $15.3 billion in 1998, and operates in the following market segments: packaging, transportation. distribution, alumina and chemicals, aluminum ingots, and building products. (www.alcoa.com. 1999)

The Denison vinyl extrusion plant where I worked is part of the Alcoa Building Products (ABP) business unit. In 1997, building and construction products accounted for 10% of Alcoa's revenues. and Alcoa (mostly an aluminum company) was the leading producer of vinyl siding in the United States. Alcoa Building Products consisted of 5 manufacturing plants and 3 distribution centers. The Denison manufacturing site was also the location of one of the distribution centers.

2.2 The Denison Plant

2.2.1 Product

The Denison site manufactured approximately 638 different vinyl siding products. The majority of these were siding panels. and the rest were accessory products used for finishing corners, windows, and trim. The products were divided into 58 product families with an average of 11 colors per family. ABP would add another 120 products in 8 families for 1999, and Denison would produce about half of these.

Denison shipped siding mainly to distributors, but also supplied vinyl to a couple of private labels. Denison was the second largest vinyl producer in ABP, but had the largest shipping territory, supplying mostly the mid-west and western United States.

2.2.2 Plant Personnel

The Denison plant employed about 350 people. The management structure is shown in Figure 2.1

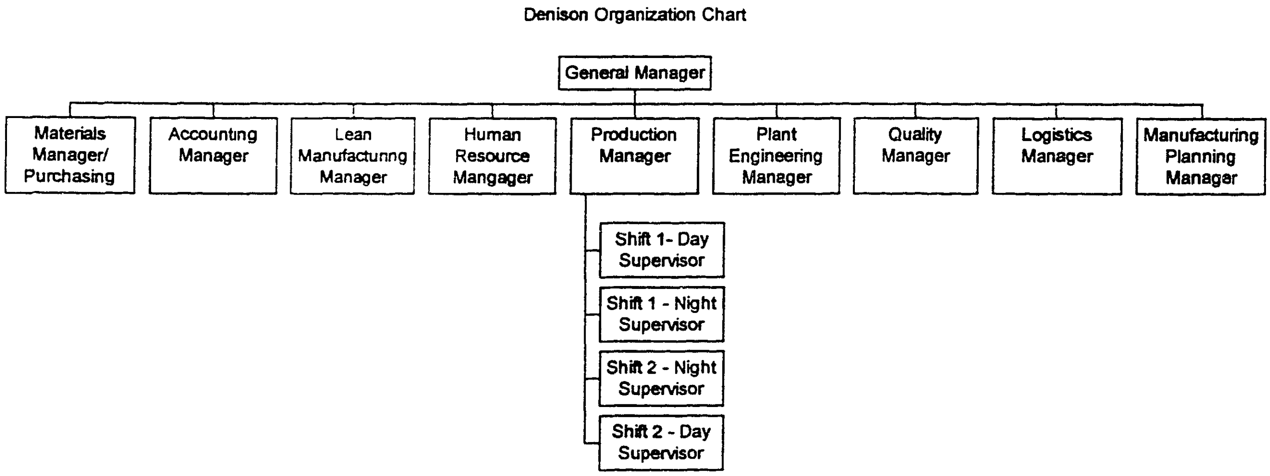


Figure 2.1: The management structure at Denison.

2.2.3 Vinyl Extrusion Process Overview

This section is a high level overview of the vinyl extrusion process, and is included to help the reader identify with the type of product that Denison deals with.

2.2.3.1 Receiving and Blending

The bulk of the material used in the extrusion process comes to the plant in rail cars, and was delivered directly to the back of the plant. The rail cars were then pumped out and the raw vinyl, and another major component, were stored in a few large silos.

The blending area then pumped the vinyl into large mixers, and added the other key ingredients including pigments for coloring. After the material had been mixed and cooled, it was pumped into smaller silos separated by color. (See Figure 2.2)

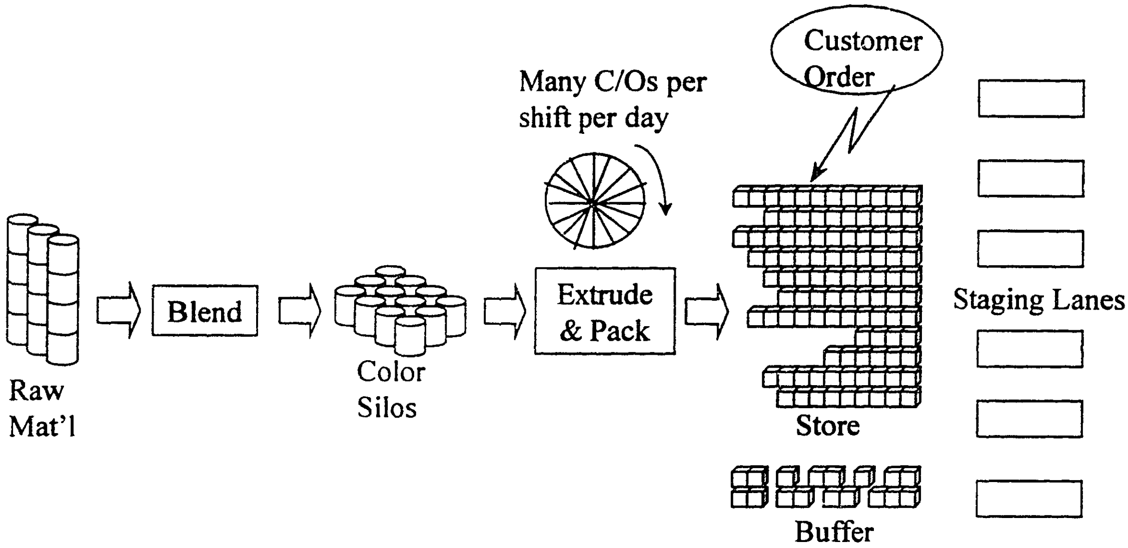


Figure 2.2: A simple schematic of the Denison Extrusion Plant.

2.2.3.2 Extrusion

By means of a vacuum system the extrusion lines could hook up to any of the smaller silos in order to run whatever color was required. The raw vinyl powder was then fed from the accumulating hopper into the feed-screws, where the friction from the turning screws and the additional heaters melted the vinyl. The vinyl was then forced through a heated die to form a pliable ribbon of vinyl approximately 15.5 inches wide and 1/16 of an inch thick. The ribbon was then pulled through an emboss roller that imprinted on the surface of the vinyl with the specified wood-grain pattern. The patterned vinyl was then pulled through a shaping fixture that formed the vinyl into appropriate profile. For regular house siding panels the profile was made to look like 2 or 3 overlapping boards, with a top nail strip for fastening the panel to the house, and a J-channel hook in the bottom for hooking into the panel below it. Upon exiting the shaping fixture, the profiled ribbon immediately entered a chilled water bath that 'froze' the intended profile into the vinyl. The hardened panels were then pulled through the punches where nail slots and weep holes were punched into the panels. After passing through the rubber wheeled puller the panel was pushed into the 'crop' that was used to cut the panel to length. The cut panel were then ready for packaging.

2.2.3.3 Packing

Typical panels were cut into 12 to 12.5 foot lengths and packed about 24 per carton, in large cartons measuring approximately 0.5 x 1 x 12.5 feet. Each box contained 2 "squares" of siding, or enough paneling to cover 200 square feet. Packing was mostly a manual labor job and the packing and gluing of the boxes was all done by hand. The packers moved the boxes from the packing table to a pallet by means of a small hoist located above the packing station. Boxes were packed 16 to 48 per pallet depending on which product was being loaded. This quantity has, in some cases, been reduced with the introduction of lean, but some of the heavy sellers are still packed with 40-something boxes per pallet.

2.2.3.4 Shipping

Denison did not have sufficient space in the production plant to warehouse and ship the product, so it was hauled in trucks to the Distribution Center (DC), a larger warehouse about a half-mile away. The DC held the products made in Denison, as well as the products shipped from other ABP plants. These products included aluminum accessories and a few products that were made exclusively at other ABP vinyl plants.

Customer orders were received 5 days in advance of the ship date, with additions made up to 48 hours before the ship time. Denison could fill most orders of locally produced vinyl within 48 hours, but needed the 5 days to make inter-plant orders for items not produced at Denison.

Because each truck that was loaded at the DC was a cost to Denison, customers were encouraged, even rewarded, to order complete truck loads. This policy promoted behavior that was actually detrimental to the implementation efforts of lean manufacturing, as it increased the unlevel nature of the demand on the production system. Customers would typically order more of each product in order to fill up their trucks, so the immediate demand on the extrusion lines, for a given product, was high but tended to be less frequent, and therefore "spiky." Another detrimental behavior, practiced by a few of the distributors, was that of the dummy order placed at the required 5 days ahead and then switched, rather than added onto, at the 48 hour mark. This practice resulted in excess production that limited the plant's ability to produce the right products at the right time. Realizing that this was an issue, the Denison plant management and customer service representatives were working to change the policy and behavior.

3 Selected Literature Review of Inventory Policy

This section is not meant to be an exhaustive review of the available literature on inventory policy, rather it is here to familiarize the reader with some of reasons that inventory policy exists, and some of the tools available for making inventory policy decisions.

3.1 Reasons for Inventory

Inventory is kept in three forms, namely raw inventory or component parts, work-in-progress (WIP), and finished goods inventory (FGI). Inventory is due mostly to system constraints (for example machine unreliability or batch processing), or to uncertainty. The matrix below shows raw inventories, WIP, and FGI and some of the common reasons for holding inventory in these three forms. (See Table 3.1) Note that batch processing and variability affect all three forms, and that FGI is affected by almost all of the drivers.

Table 3.1: Showing the drivers of the 3 forms of inventory.

	Raw inventory	WIP	FGI
Batch Processing	X	X	X
Variability	X	X	X
Queuing		X	
Customer Responsiveness			X
Forecast Error			X
Seasonality	X		X

Inventory builds up with batch processing due to each part waiting for the entire batch to be processed before the entire batch is moved on to the next process. Inventory increase due to variability can be due to demand, or process variability. Inventory can also accumulate when parts are stuck in queue waiting for the next resource to become available. Some organizations keep larger inventories on hand to guarantee that a part will always be on-hand when requested by the customer. Some inventory can be due to actual customer demand being lower than the forecast and the quantity produced in anticipation of that demand. And finally, some organizations choose not to ramp up and down with the seasonal change in demand; instead they produce at a constant rate all year and build up peak season inventories during the slow season.

3.2 Inventory Policy Models

This section discusses some of the more common inventory policy models, namely the EOQ Model, the Base Stock Model, and briefly the (Q, r) Model. The following models view production as a black box, or a single stage production system with no consideration given to WIP. Likewise, raw materials are considered an infinite supply and are not addressed by the inventory policies.

3.2.1 The EOQ Model

One of the better known inventory models is the Economic Order Quantity (EOQ) model, which is used to size reorder quantities. EOQ takes into account the drivers of inventory, and balances holding cost and setup cost in order to achieve the overall lowest cost. Figure 3.1 shows the cost functions of holding, setup and total cost.

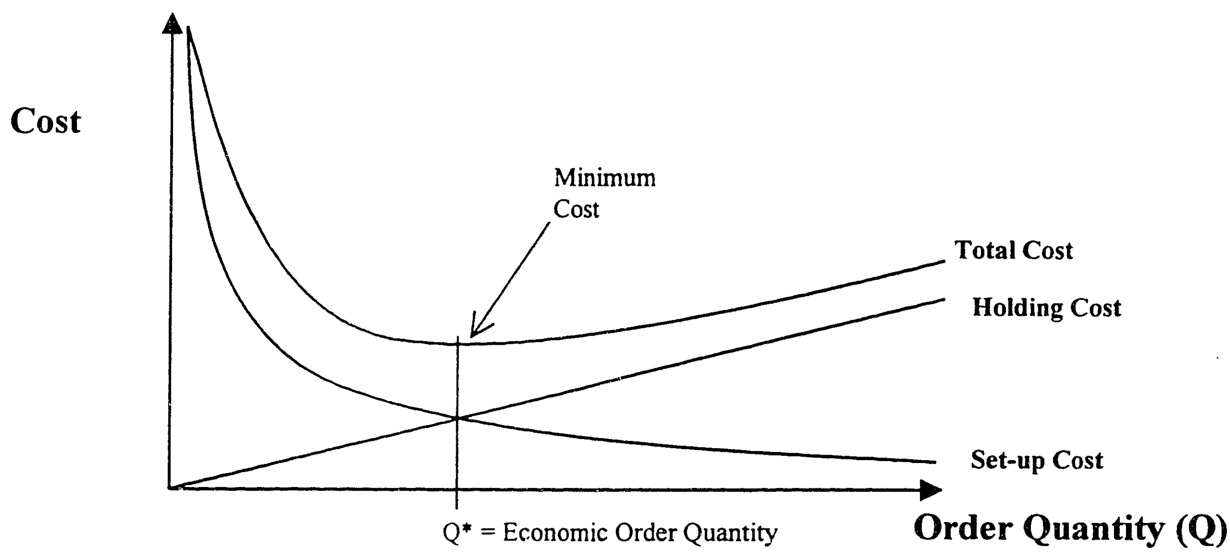


Figure 3.1: Graphically shows the meaning of the Economic Order Quantity.

As shown in Figure 3.1 the holding costs increase and set-up cost decrease as the order quantity increases. The total cost curve is the sum of the holding and set-up cost. The minimum cost value on the total cost curve is the economic order quantity (Q^*).

The EOQ Model is the following:

Where:

$$Q^* = \sqrt{\frac{2AD}{h}} \tag{3.1}$$

D = Demand rate
A = Setup cost
h = Holding cost
(See Nahmias (1997) or Hopp and Spearman (1996) for the derivation of the EOQ formula.)

Note that Q* is established using costs only. One aspect of order quantity not considered, is that as the order quantity increases the frequency of ordering decreases, and therefore the average amount of inventory on-hand will be larger, the number of times that inventory approaches a minimum is reduced, and the chances of stocking out are less. Another aspect not covered is the extreme difficulty of estimating holding and setup costs. Because of this, many find it more useful to set optimal inventory levels based on a desired level of customer service. The next model, or Base Stock Model utilizes this strategy.

3.2.2 Base Stock Model

Hopp and Spearman (1996) describe the model parameters this way, "...we consider the situation where inventory is replenished one unit at a time as random demands occur, so that the only issue is to determine the reorder point. The target inventory level we set for the system is known as a **base stock level,** and hence the resulting model is termed the **base stock model.**"

The base stock model has the following assumptions:

1. Demands occur one at a time.
2. Any demand not filled from stock is backordered.
3. Replenishment lead-times are fixed and known.
4. Single stage production with infinite capacity.
5. There is no setup cost associated with placing an order.
6. There is no constraint on the number of orders that can be place per year.

"Note that the last two assumptions imply that there is no incentive to replenish stock in anything other than one-at-a-time fashion." (Hopp, 1996) In other words the most efficient method of replenishment is to make or buy one unit for every one that I use. In effect "a base-stock control policy is a pull system." (Graves, 1988)

The base stock model for normally distributed demand is the following:

$$B = (\mu * L) + (Z * \sigma * \sqrt{L}) \tag{3.2}$$

Where:
B = the desired base stock level
L = order lead-time (= l + r, replenishment lead-time + review period)
μ = average demand (mu)
Z = the level of customer service as the number of standard deviations from the mean
(For example, at Z = 2.05, customer service should be at 98%.)
σ = standard deviation of the demand data (sigma)

For a complete description of the derivation of the base stock model see "Safety Stocks in Manufacturing Systems." (Graves, 1988)

A quick examination of the model will help the reader to reaffirm their intuitive feel that as demand, lead-time, desired level of customer service, or variability increases that the level of base stock will increase.

To increase the overall understanding of the model consider an example using the demand distribution in Figure 3.2. The average daily demand (μ), as shown in the figure, is 300 units per day. Let's assume the lead-time (L) is fixed at 2 days. The first part of the base stock model (μ * L) accounts for 600 units, and if demand is exactly 300 units per day then 600 units would last for the 2 days of lead-time. But, we can see from the distribution that demand will only be 300 units per day or less, 50% of the time. The other 50% of the time it will be higher. The second part of the model (Z * σ * √L) is the safety stock and provides the "excess" inventory to cover higher than average demand. Note that the more variable demand is, the wider the distribution will be, the larger sigma (σ) will be, and the larger the safety stock will be. If demand were exactly 300 units per day, then safety stock would not be necessary.

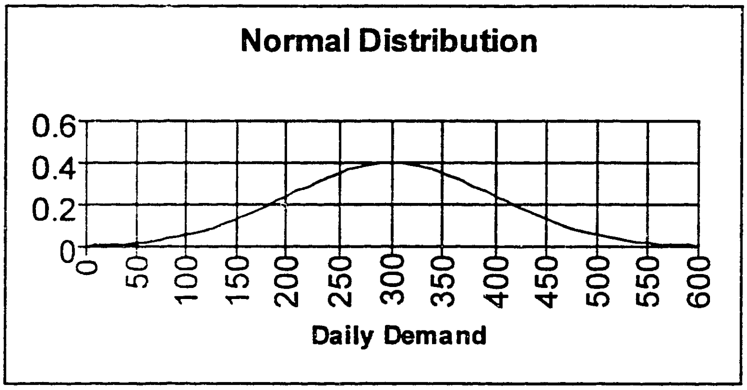


Figure 3.2. A normal distribution representing the daily demand.

If the demand distribution is truly normal then ($Z * \sigma * \sqrt{L}$) will correctly size the safety stock for most systems. However, in many cases demand is not perfectly normal and the safety stock portion of the base stock model should be adjusted by a correction factor. If we re-write the above as ($Z * \sigma * L^{0.5}$) then the generic form would be written as ($Z * \sigma * L^{q}$). The value of q will be in the range from 0.5 to 1.0. (Nahmias, 1997) The value of "q" would have to be determined experimentally.

The base stock formula is most often written as in Equation 3.2. This is due the pervasive nature of the normal distribution. However, the base stock model can be used with any well-behaved distribution. The point of the model is that enough stock is kept on hand to cover the average demand (50%) over the lead-time (e.g. $(\mu * L)$), plus the safety stock or the additional amount required to cover the demand at a higher customer service level. In other words, if I wish to fill, from stock, 95% of the orders that I receive, then I need to carry a quantity of inventory such that the probability that the amount on-hand is greater than the demand over the lead-time is equal to or greater than 0.95.

Because of its simplicity and also because it can be "extended to a range of situations" the "base stock model has been widely studied in the operations management literature." (Hopp, 1996)

3.2.3 The (Q, r) Model

Another model often used is the (Q, r) model. This model is similar to the base stock model, but takes into account the holding and setup costs. It is a useful model when one by one replenishment (as in the base stock model) is impractical. However, just as in the EOQ model these costs are extremely difficult to estimate in many situations. Note: the base stock model is just a simplified (Q, r) model with Q = 1. (Hopp, 1996)

3.3 A Comparison of the Base Stock and Lean Inventory Formulas

Analytical formulas for sizing inventory or calculating the number of kanban needed are also found in many of the reference books on lean production. (See Section 4.5.3.1 for a discussion on kanban.) The number of kanban needed in a system is equal to the amount of individual inventory items divided by the container size. For example, Toyota Production System by Yasuhiro Monden (1998) states that for a "Constant Cycle, Non-constant Quantity" system (which is what Alcoa is proposing to use) the standard quantity (base stock) is as follows:

Standard Quantity = (Daily Demand) x (order cycle + lead-time) + safety stock

or

$$\text{Total \# of Kanban} = \frac{\text{daily demand x (order cycle + lead-time + safety period)}}{\text{container size}}$$

From The Design of the Factory with a Future, by J.T. Black (1991) we find the formula for maximum inventory level to be the following:

$$M = DL + S \qquad \text{(Black, 1991, Equation 9.1)}$$

Where:
M = maximum inventory level (base stock level)
D = expected demand
L = lead-time
S = safety stock

Notice the similarity of these formulas to the base stock model discussed in the Section 3.2.2. Table 3.2 shows these formulas in a matrix for easy comparison. The base stock model is almost identical to the others except that it explicitly shows how much inventory should be kept as safety stock.

Table 3.2: A comparison of the lean production and the base stock inventory models.

	Cycle Stock	**Safety Stock**
Monden	Daily demand * (order cycle + lead-time)	Safety stock
Black	D (daily demand) * L (lead-time)	S = safety stock
Base Stock	μ (avg. demand) * L (lead-time)	$Z * \sigma * \sqrt{L}$

One final note. Regardless of the numbers found by using these formulas, one should keep in mind that the goal is to continue to reduce the parameters, e.g., lead-time and safety stock. (Monden, 1998) In other words, the first solution is only valid until the system is improved, and the system should be in a constant state of improvement.

This page intentionally left blank.

4 Overview of Lean Manufacturing

As the efforts at Denison were focused on lean manufacturing, I feel that it is appropriate to include a brief section on lean manufacturing.

4.1 The Shift to Lean

Lean production has been around a long time. In fact, Henry Ford practiced some lean production principles before he started using mass production in the early 1900s. (Liker, 1998) However, not until the Japanese car makers began to seriously threaten the "Big 3" car makers of the United States in the 1970s did American manufactures realize that maybe there was another, or perhaps better, way of manufacturing. This alternate method of manufacturing is known as the Toyota Production System[1] or Lean Production as named by Womack, Jones and Roos. (1991)

Despite being a superior production system for most situations, lean production is difficult to implement. Mass production has been the model for so many years that mass production thinking seems to be instilled in all of us, and many of the lean production principles seem counterintuitive. Part of the difficulty of applying lean is that it cannot be done in a cookbook approach. Lean manufacturing is more of "a collection of attitudes, philosophies, priorities and methodologies." (Hopp & Spearman, 1996) Many books have been written about lean, and how to convert traditional mass production to lean production. None of them is a perfect resource for all lean manufacturing problems, but collectively they provide a vast resource for the lean change agent.

Knowing that I cannot completely cover lean manufacturing in this document, I have tried to assemble some of the most basic and relevant ideas concerning the implementation of lean manufacturing. In the first section I discuss the goals of lean manufacturing. In the next section, I consider some of the people issues that affect the implementation of lean manufacturing. The next section is on some of the system stability issues, or what needs to happen before lean can

[1] The manufacturing system is known as the Toyota Production System (TPS) because of Toyota's excellent example of implementation. Note: Even though TPS is named after Toyota the car company, TPS is considered the ideal application of lean production, and Toyota's actual manufacturing may in some cases fall short of the ideal. (Liker, 61)

really be successful. The fourth and fifth sections discuss the two pillars of lean: Just-in-Time and Autonomation. Again, lean manufacturing is a complex production system philosophy, but the two pillars are the real core, and therefore merit discussion here. (See Figure 4.1)

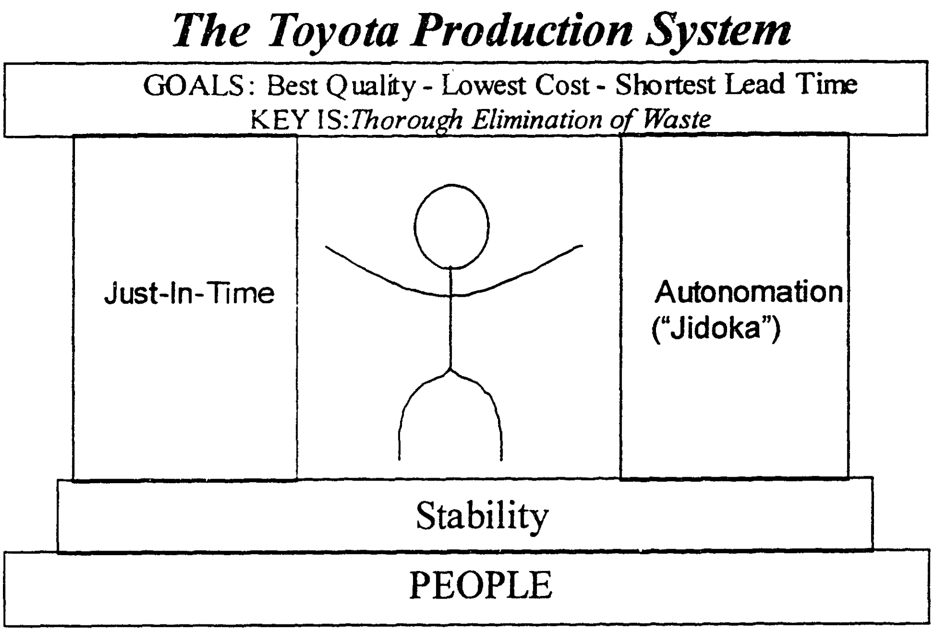


Figure 4.1: A simplified version of Alcoa's depiction of the structure of the Toyota Production System.

4.2 The Goals of Lean Manufacturing

The goals of lean manufacturing are simple. They are to reduce costs, improve quality and to improve customer service. These are all accomplished through the systematic removal of waste from the manufacturing system. In lean manufacturing there are seven categories of waste, these categories are[2]:

1. **Overproduction** means to produce more than demanded or produce it before it is needed. It is visible as storage of material. It is the result of producing to speculative demand.

2. **Inventory** or Work In Process (WIP) is material between operations due to large lot production or processes with long cycle times.

3. **Transportation** does not add any value to the product. Instead of improving the transportation, it should be minimized or eliminated (e.g. forming cells).

[2] These definitions are taken directly from the glossary on the web page for the Production System Design Laboratory at the Massachusetts Institute of Technology. (PSD Website, 1999)

4. **Processing** waste should be minimized by asking why a specific processing step is needed and why a specific product is produced. All unnecessary processing steps should be eliminated.

5. **Motion** of the workers, machines, and transport (e.g. due to the inappropriate location of tools and parts) is waste. Instead of automating wasted motion, the operation itself should be improved.

6. **Waiting** for a machine to process should be eliminated. The principle is to maximize the utilization/efficiency of the worker instead of maximizing the utilization of the machines.

7. **Making defective** products is pure waste. Prevent the occurrence of defects instead of finding and repairing defects.

The drive to remove wastes came from Toyota's different market situation in the first half of the 20th century. Because American car manufacturers could sell everything they could make, high volumes and mass production were the answers to increased revenue. In Japan however, Toyota was producing several model types at low volumes. Mass production would not work for Toyota, but they felt that if all of the waste were removed from Toyota's production system, then Toyota would be able to compete with American auto manufacturers.

4.3 People

People are the real key to any manufacturing system, but because lean is such a different system than what most people are accustomed to, extra care must be taken when helping people to understand and accept lean manufacturing. There are two important parts to the people issue. First, is the actual people, or the roles they play in the implementation of lean manufacturing. Second, is the environment in which they work.

4.3.1 The Players

There are several layers of involvement for the people engaged in implementing lean manufacturing. Below I briefly discuss four.

Leadership - Absolutely critical is leadership from the top. Success story after success story points to a leadership team that understands and pushes for lean. According to Mike Husar, who was instrumental in the conversion of Delphi Steering to lean manufacturing, "it is essential" that the plant manager have a deep understanding and involvement. (Liker, 1998)

Outside help - In most cases, outside help is necessary to aid in the conversion to lean manufacturing. Lean manufacturing is still new to many, and sometimes seems counterintuitive, so it helps to have someone who has seen how lean manufacturing is supposed to work in order to keep people on track.

Shop floor involvement - In most cases of lean manufacturing implementation, this is the real key to success. The overall vision of lean must be pushed forward from the top, but the individual elements of real implementation and success are created by those on the floor. Only when hourly personnel are involved and actively participating can efforts actually move forward.

There are two systems of thought on the best way to involve employees in the implementation of lean. The traditional model used by many Japanese consultants is the "learn by doing model." The thought is that only after employees begin to make changes and become involved in lean will they begin to understand why they are making them and what else needs to be done in order to move forward. This model works well in most situations, but in situations where there is distrust between labor and management or where there have been many "programs of the month," it is sometimes necessary to train before doing. (Liker, 1998)

Creative engineers - While many of the processes of lean are well documented and fairly easily understood, and while shop floor involvement is the key to success, there are many problems encountered in the application of lean that require the technical know-how of engineers for a solution.

4.3.2 The Environment

The type of environment into which lean manufacturing is introduced is critical to its success. Most people have heard of lean manufacturing, and many think that it, like re-engineering, is just a way to reduce headcount. While it is true that the introduction of lean manufacturing can reduce the need for personnel in certain areas, the most successful examples of lean manufacturing implementation create increase sales and plenty of opportunities for workers to move to new areas or work in the areas of newly increased capacity. Security is an important issue to workers, and the lack of it will create huge amounts of resistance to the introduction of lean manufacturing. In order to alleviate these fears many companies that choose to implement lean manufacturing also announce that no layoffs will occur due to lean manufacturing. In some cases where the company has known ahead of time that they are "too fat" they have announced layoffs before ever mentioning the introduction of lean manufacturing. (Womack, 1996)

As mentioned before, lean manufacturing concepts are counter-intuitive to most people, and there are many misconceptions about what lean manufacturing really is. Because of this, training is vital for the understanding of all employees. Introductory training is important to help people understand what lean manufacturing can do for production. After the initial training, on-the-job training (making real changes to the system) is the best kind of training, but as people run into new lean manufacturing concepts additional classroom training may be necessary. More important than what is taught or where it is taught is that employees understand the vision of where to go, and that they know that when they need more understanding, the help will be available.

The previous sentence eludes to perhaps a more "hands-off" type of approach in letting employees learn and do lean manufacturing. If employees are left alone to implement lean, in most cases, it will never happen. But where employees have been given the freedom to improve their working conditions in the course of implementing lean manufacturing, have been supported by their direct and middle management, and where upper management has clearly communicated their support, marvelous things can happen.

4.4 Stability

The second layer of Figure 4.1 is the stability layer. It is characterized by the following:

- Reliable equipment with known and practiced maintenance schedules.
- Stable processes with predictable output.
- High quality products and quality minded employees.
- Stable suppliers that are able to supply the needed components reliably. (This is not to say that suppliers must also practice lean manufacturing in order to be a supplier, but the typical company conversion to lean involves the spreading of lean to suppliers after the company has attained some level of success in their efforts.)

The stability issue is an interesting one. There seem to be two traps that some companies fall into. The first, is that of getting stuck in this phase of improving stability, and never actually getting to lean manufacturing. However, the hazard that seems more prevalent is that of jumping into calculating takt time and setting up pull lines before the system is stable. (See takt time and pull system later in this section.) Some might argue that by going to a pull system, the whole system and the people running it are forced to stabilize, and this goes along with the "learning by doing" method of lean manufacturing implementation. However, I contend that this is fraught with the danger of repeated failures and discouragement on the part of the employees. I would argue that unless the employees are already excited about implementing lean manufacturing, and unless the management team has a lot of time to spend encouraging people to keep going in the face of failure, a stable environment is a must for the implementation of a successful lean manufacturing system.

4.5 Just in Time (JIT)

JIT is the first of the two pillars of the Toyota Production System. (See Figure 4.1) The elements of JIT are detailed below.

4.5.1 Continuous Flow

Ideally, items should move through the manufacturing system one at a time. Regardless of whether this is possible, flow means that items go smoothly from one production stage to the next without any "detours into storage." (TMC, 1995)

4.5.2 Takt Time

In lean manufacturing, takt time is an important parameter that is used to set the pace of production. Takt time is the demand rate of the customer, and provides customer focus. For example, if the weekly demand for Item A is 7000 units, then the daily demand is 1000, and the hourly demand is 125 for a single 8-hour/day shift. The takt time, which is time per unit, is then 3.84 minutes. In other words, in order to meet customer demand, one Item A would have to be manufactured every 3.84 minutes or less.

4.5.3 Pull System

A Pull system is usually the first thing that comes to mind when thinking about lean manufacturing. Because there is a major difference between pull and push systems, it is worth discussing here. Push systems are the traditional mass production systems that control the input into a system. This is done with the idea that if the right amount of components and raw materials go into the start of the system, then the desired number of finished product should exit the end of the system. However--and this comparison has been made often--this is sometimes like pushing a rope, and the whole process tends to get bunched up.

A pull system is a production control system where only final assembly is scheduled. Upstream process production rates are now controlled by downstream demand. When one unit of finished product is pulled from the end of the assembly line, this sends a signal to the upstream process to pull the components to make another unit. This in turn signals the upstream component processes to make another unit and so on. Therefore, when one unit is pulled from finished goods, a chain reaction is started in which each process is signaled to begin production only when more product is needed. Until then, it remains idle, not producing excess inventory.

There are two types of pull systems, a Type A (Make-to-stock), and a Type B (Make to Order). Type "A" parts are the "high demand" parts, or standard parts that are ordered consistently and frequently. Some small amount of stock is usually kept for each type "A" part. When an order for that part is received, the part is pulled from inventory and shipped. The kanban attached to the finished part is then sent through the system to build the replacement part. This system has the advantage of being able to ship a part without having to wait for the manufacturing throughput time. Type "B" parts are non-standard, or make-to-order parts. When an order comes in, a kanban starts production on the part ,and the part cannot be shipped until it has made it through the entire manufacturing cycle.

4.5.3.1 Kanban

The word "kanban" is most often translated to mean card. A kanban is a visual signal used to trigger production. Some companies have called their lean manufacturing efforts a "Kanban system," but kanban is a tool to implement pull, not a pull system itself. In fact, a pull system can operate without kanban, but this is not as common. There are two-card and single-card kanban systems. Denison is currently using a single-card system. The kanban is attached to a pallet when it has been filled with cartons at the end of the production line. The pallet is then shipped to the Distribution Center. As soon as one carton has been removed from the pallet the kanban card is removed and sent back to production as a signal to produce and send another pallet.

4.5.3.2 Set-up Reduction

A major goal of a lean manufacturing system is lead-time reduction, enabled by setup times of 10 minutes or less. Toyota is famous for reducing the setup time of an 800-ton press, used for stamping out car hoods and fenders, to three minutes. (Monden, 1998) This is amazing considering that, at that time, it was common for other carmakers to take hours, even an entire day to complete a similar setup.

First, a definition of setup time. ***Setup time is the time from the last good part of the previous setup to the first good part of the new setup.***

The following steps and techniques for setup reduction are adapted from the following three resources: Toyota Production System by Monden (1998), The Design of the Factory With a Future by J. T. Black (1991), and A Study of the Toyota Production System by Shigeo Shingo (1989).

> **Step 1** – Identify Internal vs. External setup - Internal setup is that which can only be done when the machine is stopped. External setup can be performed at any time.
>
> **Step 2** – Separate Internal and External setup - Once the internal portion of the setup has begun it should not be interrupted by setup operations that could be performed externally.
>
> **Step 3** – Minimize the Internal setup - This requires reducing the time to change tooling at the machine, and converting as much as possible of the changeover operation from internal to external setup.
>
> **Step 4** – Eliminate the adjustment process - Changing tooling or dies may be quick, but if the required adjustment time is long then setup time is too long.
>
> **Step 5** – Eliminate the entire setup - This can be done by using the same part in multiple products, or by producing multiple parts at the same time. Multiple parts can be made at the same time for example by punching two parts with the same die, or by using less expensive multiple machines to create the parts.

While machine downtime is determined by internal setup, total setup time is still constrained by the hours available in a day. If external setups take 2 hours apiece then one worker can only do 4 setups or less in one eight hour period.

4.5.3.3 Inventory

Although the purpose of lean manufacturing is to remove waste from the *entire* production system, one of the biggest benefits, and one of the most visual changes is the reduction of inventory. I put this section here because I felt that while many lean manufacturing techniques help to reduce inventory, it is the introduction of JIT that really drives the greatest reduction. Since the purpose of this document is to discuss a method of right-sizing inventory I felt it was appropriate to emphasize the benefits of inventory reduction. The first is that it frees up cash and floor space. The second is that by reducing inventory it is easier to see what problems may exist in the production system.

A very common representation of inventory is that of a stream full of water with rocks strewn about the stream bed. The water represents the level of inventory and the rocks are the system problems. If the water is deep, or the level of inventory is high, then the problems are hidden. If the water level (inventory) is lowered, as it should be in a lean system, then the rocks (problems) are exposed and can be eliminated. (See Figure 4.2)

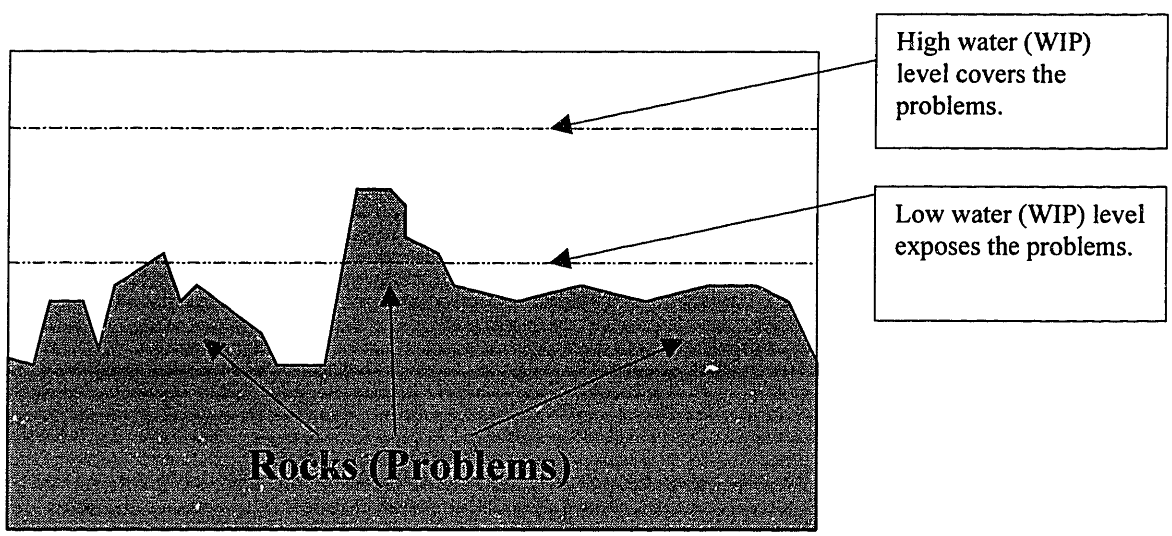


Figure 4.2: Common "stream bed" representation of too much inventory hiding production problems.

While it desirable to lower inventory level and to fix production system problems, the manner in which this is done is questioned by some. Most zealous purveyors of lean would tell us that we must lower the inventory level and "feel the pinch" so that we are "strongly" motivated to make the necessary improvements. But some question the wisdom in this and ask if it would not be smarter to probe the depths with sonar first, and remove the rocks before they cause any damage to our "boat." (Hopp & Spearman, 1996)

As I mentioned earlier, many companies have been stung by having too little inventory to effectively run their production system. By focusing on inventory reduction alone, they have missed the finer points of system stability and improvement, and have been unable to satisfy customer demand in a timely manner. Because of this, I believe it is best to continuously improve the system so that inventories may be reduced. At the same time, though, companies should use a model (like the base stock model) to correctly size inventories, and insure customer satisfaction.

4.6 Autonomation ("Jidoka")

Autonomation is the second pillar of lean manufacturing, and consists of the following elements.

4.6.1 Autonomation

Autonomation comes directly from the work that Sakichi Toyoda did with the automatic looms at the Toyoda Weaving and Spinning Company. By automating the looms to stop whenever a thread broke, Toyoda was able to free the worker from the machine. (Ohno, 1988) In many mass production facilities the machine operators are assigned a single machine to watch. This way if something "goes wrong" the operator is there, ready to shut the machine down. By having the looms shut down automatically, the worker was free to work with several looms rather than just watching one.

Autonomation is really a made up name, and is the English equivalent of Jidoka. The definition that has been given to Autonomation is "automation with a human touch." (Ohno, 1988) The purpose for the distinction has commonly been explained in two ways. One is that now machines can run autonomously and only need the "human touch" when there is a problem rather than all the time. (Hopp & Sprearman, 1996) Two, by freeing up the operator from a constant vigilance of the machine, the operator is free to do other tasks that might be more necessary or interesting. Whatever the definition, the main benefit is that each worker can be more productive.

4.6.2 Pokayoke

In lean manufacturing there are two, subtly different, methods for reducing defects in manufacturing. The first, as previously mentioned, is automatically stopping a machine when an error has occurred, thus reducing the defective parts that could be made. The second is called Pokayoke, or "error proofing" for those who prefer an English name. A pokayoke device can be used to automatically inspect parts in between manufacturing operations, or it can be used to prevent defects before they are created. For example, at United Electric in Watertown, Massachusetts, a cell that assembles pressure gages uses a pokayoke device to prevent them from incorrectly wiring a switch used in the assembly. The fixture is built to hold the switch housing for easier wiring, but the real beauty of the device is that it will not release the switch until it has been wired correctly. This guarantees that the switch is right every time.

This page intentionally left blank.

5 Inventory Problems and the New Pull System Proposal

5.1.1 Introduction of APS

In an effort to organize many previous programs and tools into a single system, top management at Alcoa created the Alcoa Business Systems (ABS). In 1996 they adopted lean manufacturing throughout Alcoa, as the unified system for manufacturing. They named the effort the Alcoa Production System (APS) after the best-known example of lean manufacturing, the Toyota Production System (TPS). It was felt that APS would improve quality, reduce costs, and shorten lead-times. The Alcoa Building Products division also began its implementation of APS in 1996, with Denison starting in the spring of 1997.

In order to facilitate the adoption of lean manufacturing, Alcoa hired YOMO Consulting, a group of consultants that had worked for Toyota or one of their suppliers in a TPS environment. Alcoa also created an in-house consulting group that was heavily involved in the implementation at various sites and could facilitate sharing of ideas. Denison was visited regularly, by Charlie Vass of YOMO, and Jeff Jackson of the internal consulting group.

Much of the effort in 1997 focused around the implementation of a pull system on four of the extrusion lines. A pull system is really at the heart of lean manufacturing, and it was felt that by implementing pull, Denison would have to take on and solve the problems that got in the way. It was hoped that this would create momentum and get the shop floor personnel involved in problem solving.

5.1.2 Inventory problems

When I arrived in the summer of 1998, Denison had just experienced a huge surge in demand and was struggling to ramp up inactive lines to meet the demand. (Denison typically inactivated a few lines during the slower winter months.) The ramp up process involved hiring temporary personnel, and it usually took several weeks to hire and sufficiently train the new employees before they could become productive. Denison was operating a make-to-stock system, and because of the lag in ramp up, production was not keeping up with the demand, and inventories were being depleted rapidly. In some cases, inventories had been depleted and production was in the mode of running the next hottest order. In this mode, the production scheduler was now scheduling the extrusion lines that had been running a pull system, and the pull system had been abandoned.

Some felt that the pull system was a failure. Those who understood lean manufacturing realized that the biggest problem was that Denison was not able to ramp up production quickly enough, but also that the current pull system had some problems and needed some improvement.

5.1.3 APS Basics

In order to make the next sections clear, it is necessary to discuss some of the vocabulary that Alcoa used to set up the APS system. Only the necessary definitions that might be different from that of other systems will be included here.

Store(s) - By definition this was inventory held at discontinuities in the system. For a vinyl extrusion process there is continuous flow, and so there are no discontinuities in the production system. In Denison the discontinuity was between production and the warehouse, so the stores were kept as finished goods in the warehouse.

Buffer(s) - "Inventory that is held in a separate location and which is used to compensate for unevenness in customer demand." (From the Alcoa Intranet)

Safety Stock - "Inventory that is held in a separate location and used to compensate for unexpected equipment or system failures." (From the Alcoa Intranet)

5.1.4 Old Pull System

This section describes the pull system that was set up in the summer of 1997.

5.1.4.1 Product/Kanban Flow

As the pallets were filled up at the end of the extrusion line, as described in Section 2, a kanban card was attached, and the pallet was sent to the production warehouse. The production warehouse was not big enough to handle all of the products shipped by Denison, so all products were then shipped to the Distribution Center (DC), about a half-mile down the road. When the first carton of product was removed from the pallet for shipping, the kanban card was removed by the DC personnel and collected at a kanban post. When the truck drivers, who shuttled the product from the production warehouse to the DC, were ready to head back to the production warehouse, they were supposed to check the kanban post for cards to return. When the cards were returned to the production line, they were brought to the "pull boards," a scheduling system designed by the original pull teams.

5.1.4.2 Pull Boards

In order to gain participation by the shop floor personnel, the original pull system design team included several extrusion line operators. The team decided that in order to further the involvement by the shop floor, the operators should have total visibility of the products that needed to be made, and the authority to decide which products or colors should be run next. To accomplish the desired visibility the team designed a pull board, which showed all of the products and colors that were run on a given line. Figure 5.1 shows a simplified pull board for a line running only one product in ten colors. Each column represented a different color. The order of the colors was a set pattern that was designed to minimize off-color scrap during color changeovers. As kanban cards were returned from production, they were loaded into the appropriate slots of the pull board from the bottom up.

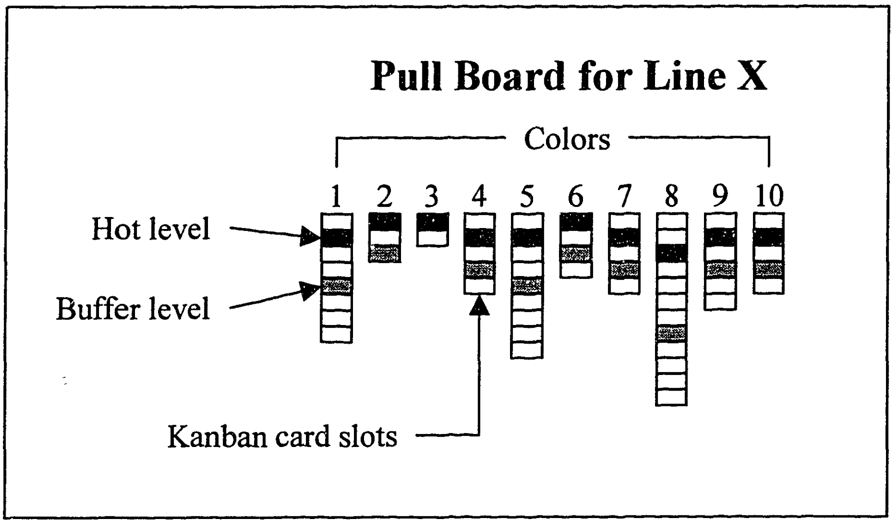


Figure 5.1: A simple representation of a single product family "pull board."

The number of slots represented the number of pallets kept in each color. The slots up to the "Buffer level" represented the store pallets, with the quantity set equal to the average demand over the expected lead-time. The slots above and including the buffer level represented the buffer pallets. These were set equal to the expected peak demand beyond the average. There was also a slot in the buffer portion that represented the hot level. If enough kanban cards were present to fill the slots up to the hot level, then that color was given priority.

The procedure was that when the operator started the shift he or she could look at the board and see if there were any "hot" items and run those first. A card in the hot slot meant that there was little or no inventory of that color left in the distribution center for filling customer orders. The next priority was to produce the colors that were up to or in the "buffer level." While the inventory was not as dangerously low as a hot item, a card in the buffer level meant that there had been a higher than average demand of that color. If none of the colors were at the buffer or hot level then the normal pattern of colors, as shown on the pull board, was produced.

5.1.4.3 Old Pull System Problems

The old pull system suffered from the following problems:

1. Not every shuttle truck driver (drivers transferring the product from the production warehouse to the distribution center) remembered to pick up the kanban cards that were at the kanban post, so the cards returned in groups making demand appear "lumpy." (Even if the drivers remembered the cards, more trucks were loaded in the morning and this made the demand appear uneven also.)

2. The uneven return of cards made it difficult to know how much product was in the system. The distribution center could be empty, but if the cards were lost, or stuck in route then the production line would not know of the shortage.

3. It was difficult to tell if the line had more demand than capacity.

4. With all of the cards available for scheduling it was too easy for undisciplined operators to make long runs of one color. This would make their job easier, but would eventually cause shortages in the other colors.

5. The system had an unknown lead-time that made calculating inventory needs somewhat more difficult.

6. The old method for determining the number of kanban (and therefore the inventory) in the system did not take into account any capacity constraints.

5.1.5 Proposed Pull System

This section describes the new pull system that was proposed in the fall of 1998.

5.1.5.1 Proposed Pull System Description

In order to solve some of the above problems, Jeff Jackson, the internal Alcoa consultant, proposed a new method for implementing the pull system. In this new system the definitions for "store" and "buffer" would change slightly. Now the store would be equal to a 95% coverage of the demand distribution (or whatever percent of customer service was desired) over the lead-time rather than just the average demand over the lead-time. In effect, a portion of what was previously called the buffer would now be part of the store. The buffer would now be set equal to the difference between the peak demand and the capacity of the line on which the product was made. In this new system the store was based on customer demand and the buffer was based on capacity constraints.

The new system would also be a "constant cycle, non-constant quantity" type system, meaning that the lead-time would be fixed. The proposal was that on "Day 1" all of the orders would be filled from the stores in the distribution center, and the kanban cards that had been removed from the pallets would be sent back to production. On "Day 2" production would gather the kanban cards and determine whether the line had sufficient capacity to handle all of them. If the quantity of cards was equal to the capacity, then production would fill all of the demand on the line. If the quantity of cards was greater than the line capacity, then production would fill the excess demand with pallets out of the buffer, and produce the rest of the pallets on the line that day. If the quantity was less than capacity, then the line could: 1) use the extra capacity to refill pallets previously pulled from the buffer stock, 2) shut down early for maintenance or kaizen, or 3) help with the excess demand from another line. See Figure 5.2 for a flowchart of this process.

As mentioned above, the new pull system allowed the lead-time to be fixed. With the buffer available to handle excess demand, 100% of the kanban cards pulled on Day 1 were matched to a full pallet and sent back to the distribution center on Day 2. Therefore, replenishment lead-time was equal to one day. Because there was another day's worth of time to pull product, collect kanban and return them to the distribution center, the total lead-time was two days. This fixed lead-time now made it possible to easily use the base stock model to size the store and buffer inventories for each of the lines.

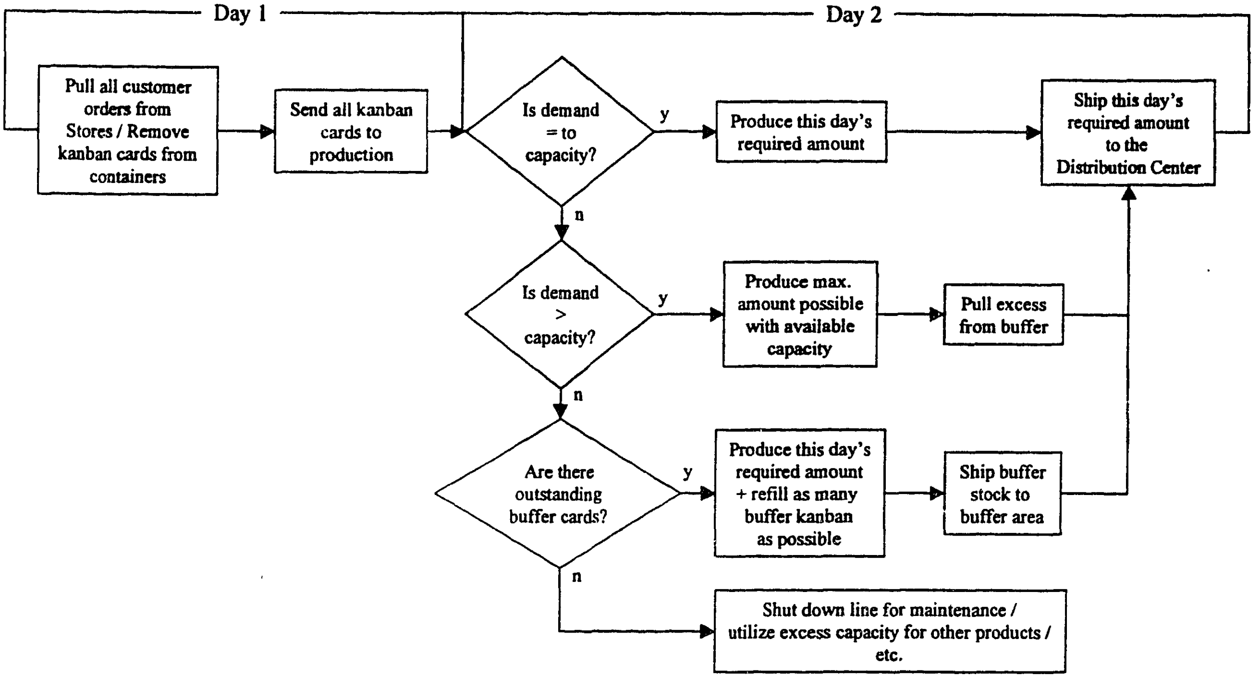


Figure 5.2: A flow chart representation of the proposed pull system.

5.1.5.2 Proposed System Benefits

The new system would have the following characteristics: (Please refer to Section 5.1.4.3 for a comparison.)

1. Because the kanban cards were only required once each day in a group, there was no dependency on the drivers to return them frequently. [However, if Denison wanted to shorten lead-time (which could reduce inventory levels) then it would be necessary to create a system to overcome this problem.]

2. By appropriately sizing the store and buffer inventories, and keeping the store stocked by using the buffer when necessary, the chances of stocking out were reduced and hot orders would become less of an issue.

3. By having to estimate line capacity on a daily basis in order to determine the number of pallets to pull from the buffer, production would quickly learn what the true capacity of the lines was and would be able to immediately see the effects of improvement activities.

4. Line operators were able to schedule the line only once per day and then would have to stick to that schedule. Thus, cheating by making long runs of one color would be less likely, and shortages would be reduced or eliminated.

5. The system had a known lead-time that made calculating inventory needs straightforward.

6 Sizing Inventory in Denison

This section contains the specifics about how I applied the base stock model at the Denison extrusion plant in order to size the finished goods inventories.

6.1 *Inventory Sizing Approach*

The following are the steps that I took on my internship to be able to apply the base stock model for sizing inventory at the Denison plant.

1. Characterize demand.
2. Characterize plant capacity by extrusion line.
3. Use a simple spreadsheet simulation to find the actual inventory needed, based on past demand data.
4. Use base stock formulas to size Stores and Buffers.
5. Verify base stock solutions with simulation data.

6.2 *Demand Characterization*

I owe a special thanks to Scott Jacobsmeyer for understanding the value of data collection. Scott began keeping shipping information in January of 1997. Most of the data that I used in my plant analysis was from the data collection that he started. Shipping data was used as demand data since there was no direct demand information kept anywhere in the database. It was felt that the difference between shipping data and true customer demand data was insignificant.

6.2.1 Seasonal Trends

Vinyl siding is very much a seasonal product, as it is only installed during the warmer months of spring, summer, and fall. Figure 6.1 shows a typical yearly demand pattern. The ramp-up and ramp-down phases of the year sometimes show some variability from year to year due to incentive programs implemented to encourage early buying, but the peak summer months are somewhat more predictable.

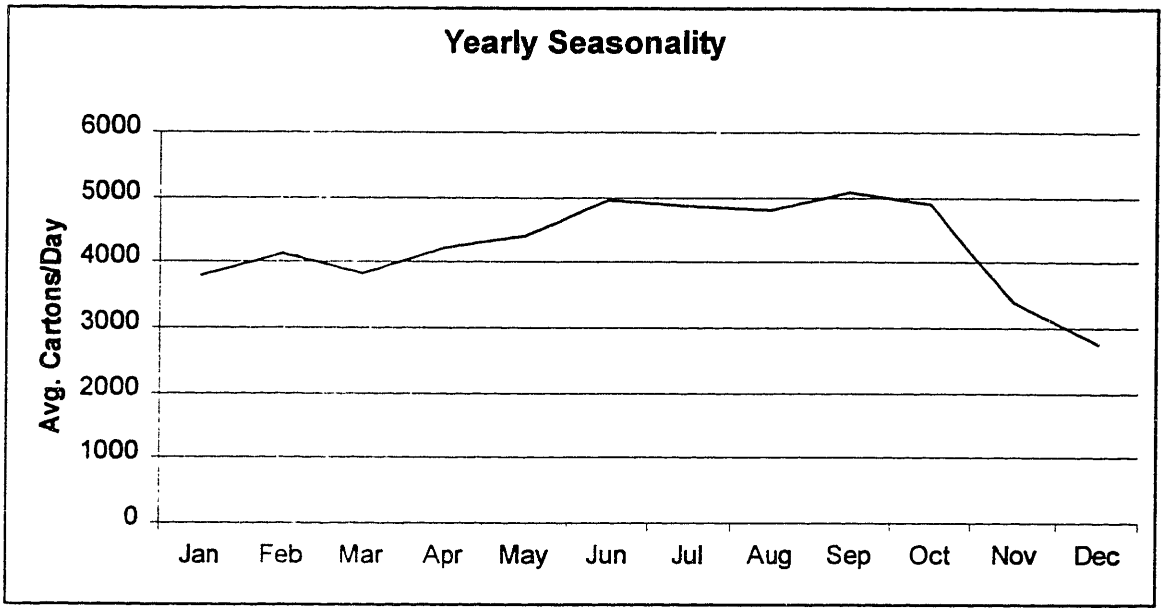


Figure 6.1: Showing the seasonality of the demand for vinyl siding.

Other types of purchasing incentives and habits influence the weekly demand pattern also. Distributors typically prefer to receive the vinyl shipments on Friday, for weekend unloading and availability, or on Monday for availability in the new business week. Backing up the three days of shipping time, we see that the peak demand days on the Denison Distribution Center were on Tuesdays and Fridays. Figure 6.2 shows that in 1997 the Friday peak was especially pronounced.

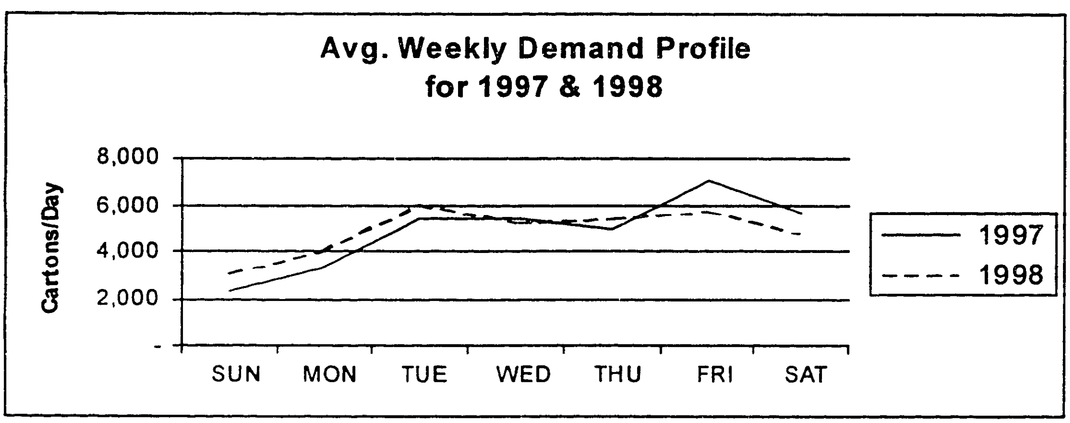


Figure 6.2: The typical weekly demand patterns for 1997 and 1998.

In 1998 the shipments were more evenly distributed during the week. The large Friday peak was gone, and shipments in the early part of the week had increased. These changes had been brought about by the efforts of the Customer Service Department to shift some of the shipping demand off of the peak days.

While there was an obvious yearly and weekly pattern, I found no sustained monthly pattern (such as an end of the month increase) in sales in the data.

6.2.2 Demand Variability

While the average demand for the days of the week, or months of the year tended to show consistent patterns, the daily demand was widely varied as shown in Figure 6.3. Figure 6.4 shows the distribution for the same daily demand data that is shown in Figure 6.3 As mentioned earlier, a major driver of inventory is the variability of demand. Because of this, any efforts that Alcoa can put into making demand more constant from day to day can greatly reduce the amount of inventory required to maintain adequate customer service levels.

One of the major goals of the Alcoa lean manufacturing effort was to convert to a make-to-order production system. We can see from Figure 6.3, that without aggregating demand over multiple days, or keeping significant inventories, that the plant capacity would have to be close to 8000 cartons/day, which is significantly more than Denison's current capacity.

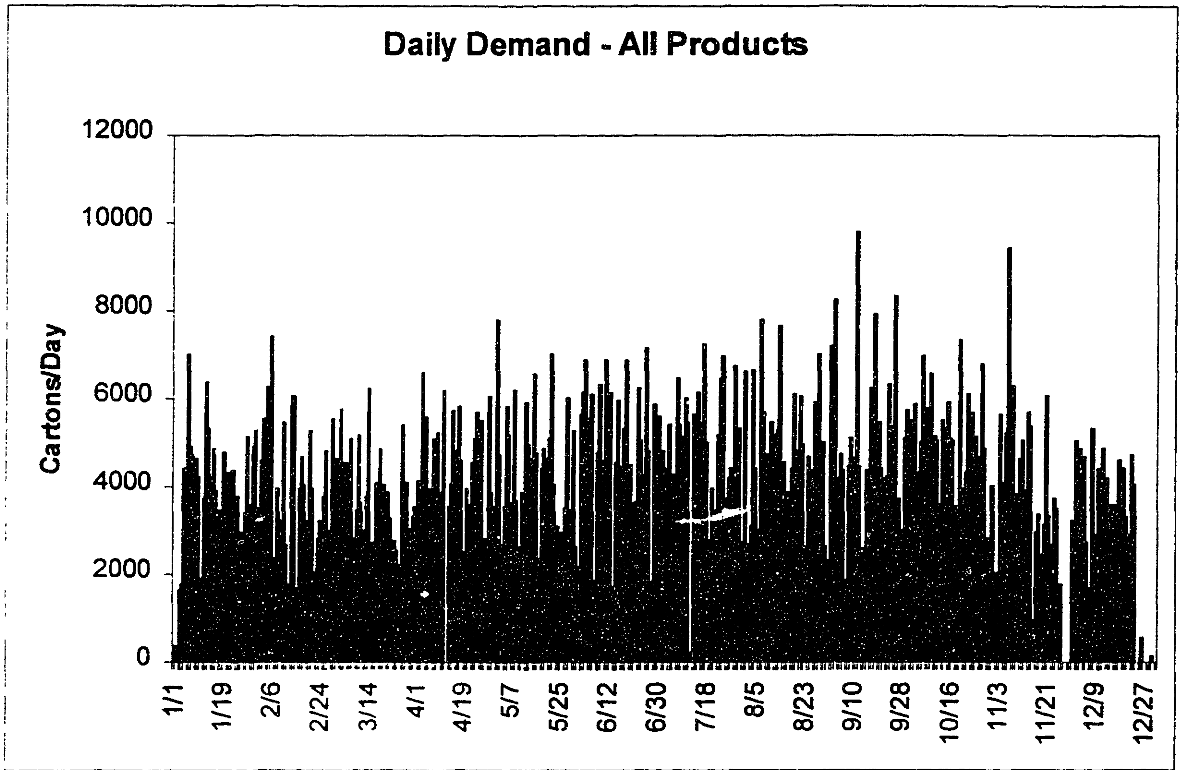


Figure 6.3: Shows the variability of the daily customer demand for 1998.

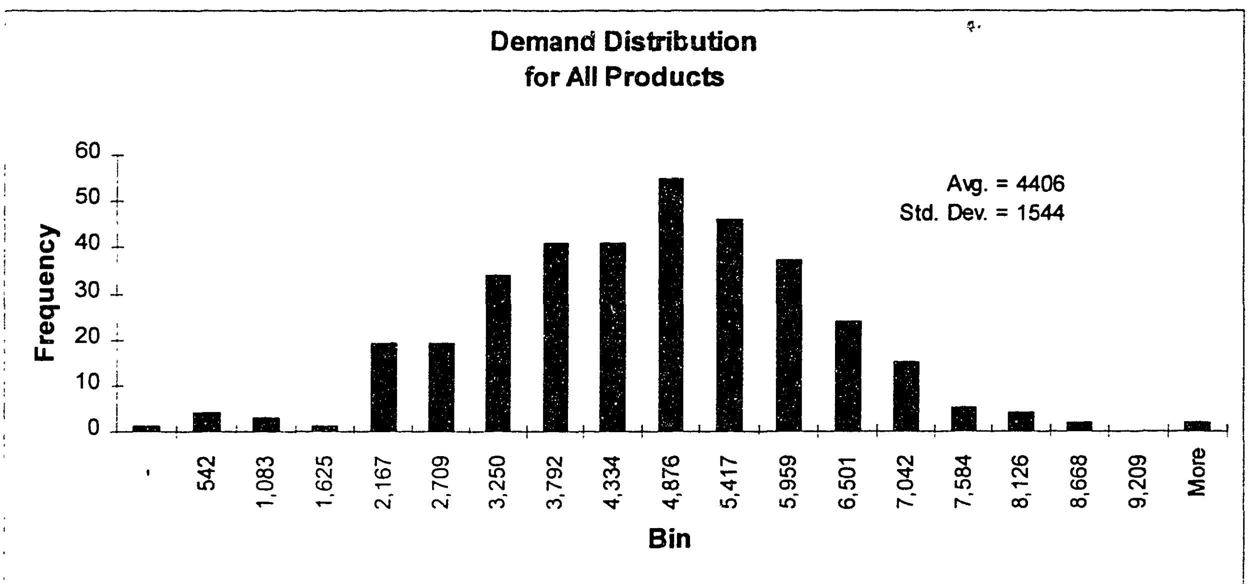


Figure 6.4: The daily demand distribution (minus holidays) for all Denison products in 1998.

6.3 Plant Capacity Characterization

From earlier sections we recall that the base stock model assumes no capacity constraints and that inventory levels are therefore set regardless of capacity. Also mentioned earlier, store levels were set to handle customer demand and its variability only. Buffer, on the other hand, was dependent on available capacity. Because of this dependency, the available capacity at Denison had to be determined.

6.3.1 The Proper Unit of Measure

The Denison plant had 16 extrusion lines, each with roughly the same throughput capacity. The plant management did the annual plant capacity plan in pounds, and it was estimated that the absolute maximum output was 149 million pounds per year, excluding any downtime. But the daily inventory management (and therefore the intuitive understanding of output) was done in number of cartons. The total plant output was approximately 5000 cartons/day, or 312.5 cartons/day per line. However, each of the 16 lines had a different output that varied from 200 to 400 cartons /day, depending on which products were being run on the line. I realized that even though carton counts were completely familiar to those in the plant, I would not be able to use them to establish individual line capacities, and I needed line capacities in order to determine the appropriate buffer size.

I decided that since I could not use pounds or cartons that I would use time as a common measure of available capacity. The first step was to use the demand data as discussed in Section 6.2, to find the demand in minutes for each of the products. I did this by multiplying the average demand (cartons/day) for each product by the Cycle Time (minutes/carton) for each product to find the average demand minutes/day. (Cycle time in this case refers to the time to fill one carton of product at the end of the line, and not the time from order to ship.) Fortunately, as we were converting to lean, Cycle Time (CT) became an important metric, and we had figured out a way to find a CT for each product using a simple database query. The CT was calculated as shown in Equation 6.1. With the average demand minutes/day I was ready to calculate the individual line capacity.

$$CT = \frac{(Total\_Machine\_Runtime\_Minutes) - (Machine\_Downtime\_Minutes)}{Total\_Good\_Cartons} \qquad (6.1)$$

6.3.2 Finding Line Capacities

With the plant running 24 hours per day I knew that there were 1440 minutes per day of possible run time. With a plant average uptime of 86.8%, each line should have 1250 minutes of uptime to make product. However, the number of minutes lost to changeovers was highly dependent on which and how many products were run on the line. What I needed was a simple way to determine which products would be run on each of the lines so I could calculate the time lost to changeovers and be able to determine the available capacity. What I created was the Line Balance Spreadsheet Tool. This tool helped me to quickly balance the workload across the 16 lines by keeping track of the time needed to make the assigned products and the time required to make the changeovers from product to product and color to color. The result of the Line Balance Tool was not only a balanced work load for each of the 16 extrusion lines, but also a line capacity for each line, in cartons per day. See Appendix A for an explanation and view of the Line Balance Spreadsheet Tool.

6.4 Spreadsheet Simulation

The next step was to analyze the daily demand on production using the daily shipping information (customer demand) from the distribution center. Because Denison was operating a make-to-stock system and because they were producing in batches (pallets), the daily customer demand was not equal to the daily demand on the production system. What we needed to know was how much inventory (stores) we needed to keep in the distribution center in order to make sure we could always make our shipments (stores). We also needed to know how much inventory had to be kept on-hand to make sure that production was always able to re-supply the distribution center (buffers).

6.4.1 Spreadsheet Simulation Description

To accomplish this, I created a spreadsheet simulation tool. The spreadsheet was able to take up to seven months of raw demand data (in cartons per day), convert it to pallets per day, and then calculate the required number of pallets for the stores and buffers for all of the products. The spreadsheet tool was divided into five major sections, and these are described briefly below.

Input/Output - This section had places for required input such as line capacity, initial inventory quantities and a place to specify which colors of the product would be included in the buffer. (It was decided to hold buffer inventory in the most popular colors in order to reduce the number of required storage locations. The total number of pallets included would be the same, but fewer warehouse access points were needed for removal and storage of the buffer pallets.) The results of the spreadsheet model (store and buffer quantities) were also in the top section for easier viewing.

Raw Data - Raw daily demand data (cartons/day per product) from the database were placed in this section.

Partial Pallets - Because the raw data were in cartons/day and all of the stores and buffers were calculated in pallet quantities, the raw data had to be converted. Also, partial pallets had to be tracked in order to subtract customer demand from the partials before calling for a new pallet to be produced. Failure to track partials led to a demand on production almost twice what it should have been.

Signals - Each time a partial pallet was used up and a new pallet was tapped into in the distribution center, a kanban card was sent back to production. The spreadsheet tool also kept track of when a new pallet would be tapped into and the "signals" that were generated were recorded in this section of the spreadsheet. If the daily customer demand could be filled from a partial pallet then no signal was generated.

A sum of the day's total number of signals gave us the demand on the production system. By subtracting the line capacity from the daily production demand we could find the daily need for buffer inventory. We did this by tracking daily the cumulative inventory shortfall. Each day the shortfall was added to the previous day's shortfall in order to keep a running total. If the daily demand on production was less than capacity then some of the shortfall could be "worked off." The buffer was set to the maximum value of the shortfall over the simulation run.

Two-day Sums - The signals in the previous section represented the daily demand on the production system. However, we needed to know how much stock we needed to have on hand in order to satisfy all of the customer demand. Because of the fixed two-day lead-time, we knew that we needed to have two days worth of inventory on-hand. By summing the signals over the lead-time (two days) we could find the maximum two-day sum and set the store size to that amount. In this way we knew that demand would never exceed our stores, and we had 100% coverage.

6.4.2 Simulation Problems

The original intent of the simulation was to find the solution to the question of how much finished goods inventory to keep on-hand. There were, however, two problems with the simulation that precluded it from being used on an ongoing basis. One, it only calculated 100% coverage for all inventory needs. Obviously, this level of coverage was too high and would be needlessly costly to maintain. Problem two was that even though the spreadsheet was fairly easy to use, it was very large and slow. It was also somewhat intimidating because of its size, and required extreme care when making modifications because of the large number of formulas in the spreadsheet. Although the simulation did not make a good tool for regular use by the Denison personnel, it was a good tool for me to get an understanding of the inventory needs, and eventually I used it to verify the FGI solutions I later generated using the base stock model.

6.5 Applying the Base Stock Model to the Data

In the following sections I will describe the base stock model spreadsheet, discuss the specific mathematical formulas used for calculating stores and buffers, demonstrate how I verified the results, and finally, discuss how to use the model to determine inventory levels from forecast data.

6.5.1 The Base Stock Model Spreadsheet

Appendix C shows a snapshot of the Base Stock Model Spreadsheet.

6.5.1.1 Input Section

Box (1) of the spreadsheet is the input area where the user specifies the customer service level for the stores and the buffers, the number of days of lead-time, and the available capacity in cartons/day.

Service Levels - As seen in Appendix C, the service levels are set to a percentage equal to the desired fill rate. In other words, this is the percent of demand that can be shipped from the stores, and not backordered. Below are some key points concerning the service levels.

- Service levels must be set lower than 100% to keep the formulas from "blowing up."
- When matching the base stock model results to the spreadsheet simulation results I found that the buffer service level tended to be slightly lower than the store service level. For example, when the store level was set at 99.95% the buffer service level was most accurate at 99.5%. Recall that the simulation provides for a 100% fill rate for the time period of the data loaded into the model.
- Because the formula used to calculate the buffer inventory levels squares the service level quantity, buffer service levels are sensitive to the service level. This will become evident later. See Equation 7.3.
- In one experiment the data were cleaned up, for one of the extrusion lines, by removing the high-end outlying points. When these data were loaded into the simulation and the base stock model, it showed that the matching service levels for the base stock model were slightly lower and closer together. (Store - 99.6%, Buffer - 99.5%)

Lead-time - This is the order lead-time. The time from when the product is pulled from stock until it is replaced. For the current pull system proposal this will always be 2 days. Key points:

- Lead-time is a big driver of inventory, and future designs should look for ways to reduce it.

Capacity - This is the capacity of the single line being considered. It is measured in cartons/day. Key points:

- Currently, the best way to get this is with the Line Balance Tool, or by experience. In the future, this quantity should be measured and tracked.
- At line utilizations above 85% the spreadsheet simulation and the base stock model spreadsheet tend to diverge in the results for stores and buffers.

6.5.1.2 Information Section

Box (2) is some useful information about the current raw data in the area below Box (3).

Total Avg. - This is the average of the daily demand totals for the line under consideration, in cartons/day. (This is equal to the sum of the averages of the individual products.)

Std. Dev. - This is the standard deviation (in cartons/day) of the daily demand totals for the line under consideration.

Weighted Avg. Ctns/Skid - Because the number of cartons per pallet was different for each of the products, I had to find the weighted average. I could then divide total buffer carton quantity by the weighted average to find the number of buffer pallets.

% in Buffer - Alcoa had determined that buffer should be kept in the most popular colors as represented by 60% of the total demand data. So, if the color white is very popular in one product family and 60% of the total production volume is white then buffer stock will only be kept in white. If, on the other hand, no colors dominate then buffer may be kept in many colors. The amount of buffer is dependent on the buffer formulas only and does not change, regardless of how many colors are kept in the buffer. The user determines which colors are to be included in the buffer and "turns them on" by placing a "1" next to the desired color in the column titled "Buffer," directly below Box (2).

6.5.1.3 Results Section

Finally, Box (3) shows the totals for the amount of stores and buffers calculated in the first two columns on the left titled "Store Skids," and "Buffer Skids."

Total Store - This is the sum of the data in column A, under the title Store Skids.

Buffer - This is calculated using a formula that I derive in a following section.

Total - This is the total of the Store and Buffer inventory levels.

6.5.2 Data Section

Store Skids - These are calculated from the base stock model [$B = (\mu * L) + (Z * \sigma * \sqrt{L})$] using the average and standard deviation for each product. The average and standard deviation are also found in the data section, in the appropriately labeled columns.

Buffer Skids - These are weighted percentages of the total buffer as found in the results section. The average demands are used as the weights, and the **Buffer?** column determines whether a particular product will be included.

Buffer? - This is explained in Section 6.5.1.2.

Raw Data - This is the daily demand, in cartons/day of each of the products under consideration. These data come from a database query.

6.5.3 Determining Stores

The stores were calculated for each of the individual products (color by color) using the base stock model [$B = (\mu * L) + (Z * \sigma * \sqrt{L})$] as discussed in Section 3. The results of these calculations are found in the Data Section in the column labeled Store Skids.

Please note that the formula used assumes a normal distribution. This assumption is only valid for some of the more popular products whose demand patterns demonstrate normal behavior. The base stock model does not require a normal distribution. In Hopp and Spearman (1996) on page 78 is an example of the base stock model with a poisson distribution.

6.5.4 Determining Buffers

The buffer stock was kept on hand to supplement the production when production had insufficient capacity to produce all that had been pulled from the distribution center the previous day. In order to determine the buffer inventory required due to capacity limitations, buffer was set to the difference between the maximum demand and capacity over "n" consecutive days. The formula for maximum demand is just the base stock model $B = (\mu * n) + (Z * \sigma * \sqrt{n})$ with "n" in place of the lead-time (L). The capacity over "n" consecutive days is C*n. In other words:

Buffer(B) = capacity shortfall = Maximum Demand - Total Capacity, or

$$B = (\mu * n) + (Z * \sigma * \sqrt{n}) - C * n \qquad (7.1)$$

Where:
Number of days = n
Average demand = D

Number of standard deviations = Z
Standard deviation = S
Daily capacity = C

Figure 6.5 shows the capacity shortfall for an example where: $\mu = 90$, $C = 100$, $Z = 2$, and $\sigma = 30$.

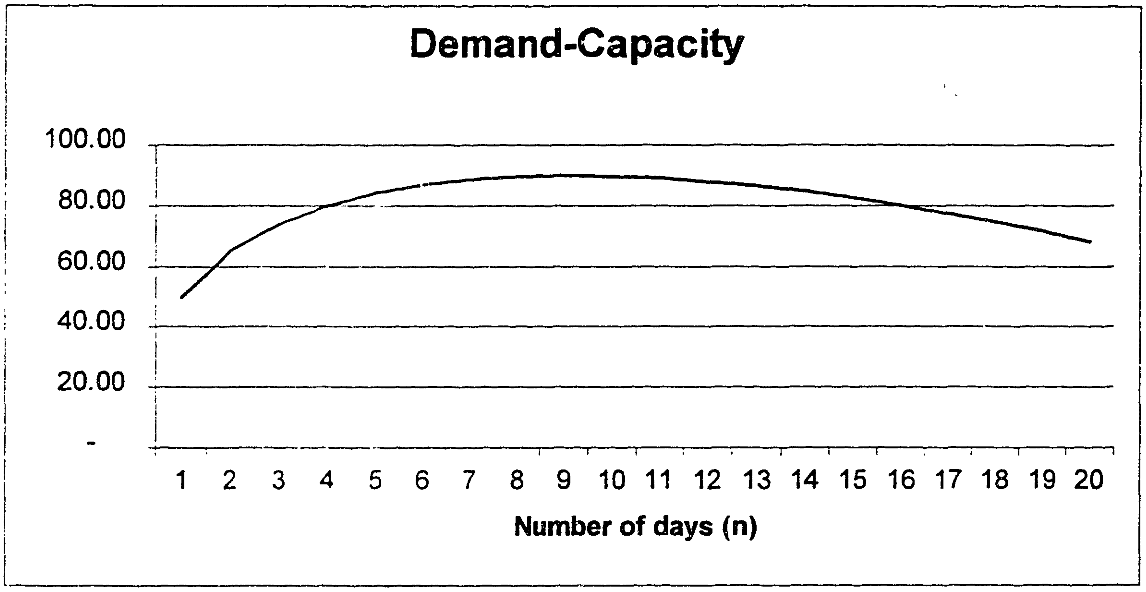


Figure 6.5: An example of the buffer requirement curve over "n" consecutive days with n = 1 to 20.

At some value of "n" the shortfall will be maximized. For this example, this occurs when n = 9, where the shortfall is 90; thus, we set the buffer, B = 90. In order to not have to graph each set of data to find the value of "n" at which "B" was maximized I took the derivative of Equation (7.1) with respect to "n," set the equation to zero and solved for "n." This value of "n" would be the number of days at which the value of "B" would be maximized in the generic case. See Appendix B for the derivation. The results from Appendix B are shown below as Equation (7.2).

$$n = \left(\frac{Z\sigma}{2(C-\mu)} \right)^2 \tag{7.2}$$

For our example $n = \left(\frac{2 * 30}{2(100 - 90)} \right)^2$ yields n = 9. Substituting n = 9 into Equation (7.1) yields

$B = (90 * 9) + (2 * 30 * \sqrt{9}) - 100 * 9 = 90$, which is the same result we get from Figure 6.5.

Next, I substituted Equation (7.2) back into Equation (7.1) to find the maximum buffer quantity for the generic case. See Appendix D for this derivation. The results of Appendix D are shown here as Equation (7.3).

$$MaxB = \frac{Z^2 \sigma^2}{4(C - \mu)} \qquad (7.3)$$

For our example $MaxB = \frac{2^2 30^2}{4(100 - 90)} = 90$, the same answer as before. Equation (7.3) is used in the Base Stock Model Spreadsheet to calculate the total number of cartons of buffer stock. The number of buffer pallets is found by dividing the number of cartons by the weighted average cartons/pallet value.

6.5.5 Verification of the Results

In order to verify the validity of the base stock model results (and the assumption of normal demand), I ran a series of comparisons of the results from the base stock model with those of the spreadsheet simulation. I used only the 5 extrusion lines that were running the products with the highest average demands and the most normal distributions. Since the spreadsheet simulation was highly accurate, but only gave 100% coverage results, I bumped up the service level numbers to 99.95% for stores and 99.5% for buffers on the Base Stock Model Spreadsheet. (See Section 6.5.1.1) In all cases, the difference in the total number of pallets to be kept in inventory was within acceptable limits. See Table 6.1. This test gave good results and showed that the Base Stock model was a valid method for finding the store and buffer inventories at Dension.

Table 6.1: Results from the comparison tests.

	Spreadsheet Simulation			Base Stock Model		
Product	**Store**	**Buffer**	**Total**	**Store**	**Buffer**	**Total**
WGV40	47	18	**65**	49	18	**67**
BW40, MB40	65	18	**83**	59	19	**78**
DBW45	106	40	**146**	113	43	**156**
PTS12	93	43	**136**	89	26	**115**
LFP40, TRM40	106	35	**141**	91	28	**119**

As mentioned in Section 3.2.2 the base stock model can be adjusted for less than perfect distributions, and the model was re-written as follows: $B = (\mu * L) + (Z * \sigma * L^q)$ where "q" is equal to 0.5 to 1.0. In the spreadsheet implementation the value of the stores and buffers can be adjusted for the distributions of the different products or lines by changing the service levels.

7 Conclusions and Recommendations

As stated in Section 1.2, the objective of this thesis is to show that the base stock model is compatible with lean manufacturing, and is an acceptable model for determining the appropriate levels of finished goods inventories at the Denison site.

7.1 Compatibility of the Base Stock Model and Lean Manufacturing

Not only are the base stock model and lean manufacturing compatible, but they are also complementary. Section 3 shows that the base stock model structure is identical to the formulas found in well-known reference books on the application of lean manufacturing. The advantage of the base stock model, however, is that it explicitly calculates the amount of safety stock. The lean books usually just state that some safety stock should be held. The base stock model, like lean, assumes one at a time replacement in a pull environment. The base stock model can be modified to consider multi-stage production, but the most fundamental base stock model assumes that production is a single stage. Because production at the Denison plant occurs in a continuous flow (at least in extrusion), the simple case holds up well without modification.

The advantage of applying the base stock model in a lean manufacturing framework, is that lean manufacturing provides a holistic method for reducing the system parameters that increase the need for inventory. Looking at the base stock model, one can see that reducing the lead-time or the variability will reduce the base stock level, but the model provides no clues about how to do this. The Toyota Production System, or lean manufacturing, or APS, or whatever you wish to call it, is a nice cohesive set of ideas that works very well at eliminating waste, and reducing the system parameters that increase the need for inventory.

7.2 Conclusions

The following points are the conclusions that I have reached as a result of this work.

- The base stock model and lean manufacturing are compatible.
- The base stock model works well at the Denison site for sizing the inventories of the more normally distributed products.

- The base stock model can be adjusted for non-perfect normal distributions.
- The base stock model can be re-written for other distributions such as the poisson distribution.
- The standard form of the base stock model as used to calculate the *stores* is fairly robust to non-perfect distributions.
- The formula used to calculate the *buffer* is less robust because of its sensitivity to customer service level. This is due to the Z^2 term in that formula.
- It is better, for customer satisfaction, to have appropriately sized inventories, rather than to arbitrarily reduce them and then try to improve the system to make it work. Improve, then reduce.
- The simulation worked well in a 100% customer service level situation, but not at any lower level, and not with forecast data. However, the base stock model can be used at service levels of less than 100%, and because the base stock model only requires the average demand and the variability, it can be adapted to use with forecast data.
- The work done on this internship and with the base stock model assumes a constant lead-time. A constant qty/non-constant cycle system would require a different methodology. The base stock model can be used with a non-constant lead-time but the lead-time variability must be taken into account in the formula.
- Someone who is very familiar with the demand patterns of the products (such as a scheduler) might be more accurate or faster at setting appropriate inventory levels without a model, but only in a static environment. Once the system changes, as it will with the implementation of lean manufacturing, the experience of the scheduler becomes less useful.

7.3 Recommendations

As mentioned several times throughout this document, inventory levels are greatly inflated by long lead-times and by demand variability. Every effort should be made to reduce these parameters.

The fixed lead-time of the proposed pull system makes using the base stock model easy. However, I believe that this lead-time is unnecessarily long and could be reduced by adopting another type of pull system (non-constant cycle, constant quantity), or by completing the product shipping, kanban return and production cycle more often than once per day.

Because all of these formulas are dependent on customer demand data, Alcoa should improve the database structure so that only true customer orders can be queried, or devise a better method for tracking true customer demand. (The current database includes non-order adjustment transactions that can distort the true customer demand.)

Because level demand is extremely helpful in reducing inventory, Alcoa should continue to work with customers and the ordering policies in order to promote more beneficial ordering behavior.

This page intentionally left blank.

References

Alcoa Web Site, www.alcoa.com, 1999.

Black, JT., The Design of the Factory with a Future, McGraw Hill, 1991.

Graves, Stephen C., "Safety Stocks in Manufacturing Systems", Journal of Operations Management, Volume 1, pp. 67-101, 1988.

Hopp, Wallace J., Mark L. Spearman, Factory Physics, Foundations in Manufacturing Management, Irwin McGraw Hill, 1996.

Liker, Jeffery K. (Editor), Becoming Lean, Inside Stories of U.S. Manufactures, Productivity Press, 1998.

Monden, Yasuhiro, Toyota Production System, An Integrated Approach to Just-In-Time, Third Edition, Engineering & Management Press, 1998.

Nahmias, Steven, Production and Operations Analysis, Third Edition, Irwin, 1997.

Ohno, Taiichi, Toyota Production System, Beyond Large-Scale Production, Productivity Press, 1988.

Production System Development Laboratory (PSD), http://lean2.mit.edu/decomposition/glossary.htm, PSD Website, 1999.

Shingo, Shigeo, A Study of the Toyota Production System, Productivity Press, 1989.

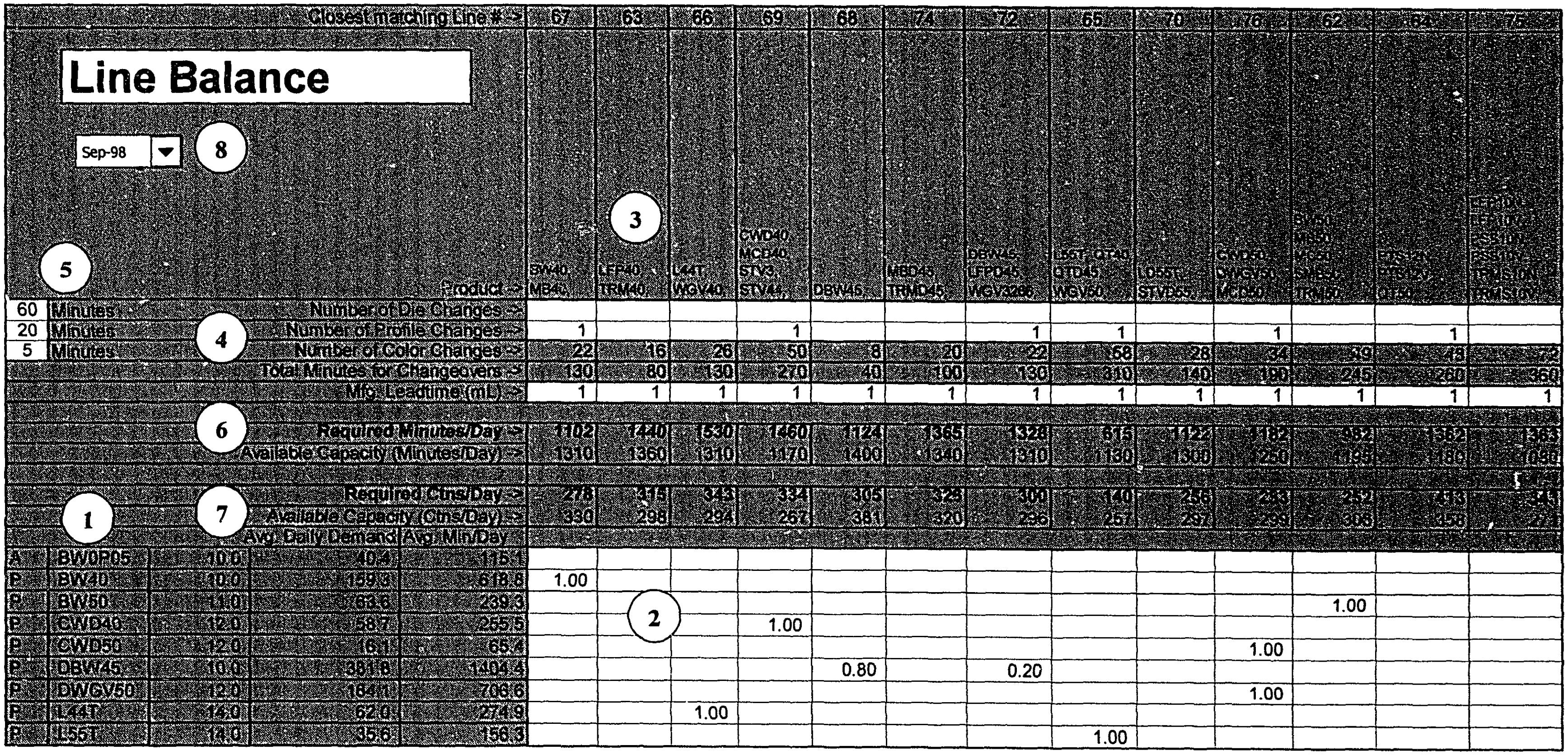
Toyota Motor Corporation (TMC), "The Toyota Production System", Toyota Motor Corporation, 1995.

Womack, James P., Daniel T. Jones, and Daniel Roos, The Machine that Changed the World, The Story of Lean Production, HarperPerennial, 1991.

Womack, James P., Daniel T. Jones, Lean Thinking, Banish Waste and Create Wealth in Your Corporation, Simon & Schuster, 1996.

Appendix A - Line Balance

A snapshot of a portion of the Line Balance spreadsheet tool, used for balancing the workload among the lines, and for determining the individual line capacities in cartons/day. See the description below. (Some of the right portion of the spreadsheet is missing, but is not important for the description.)



Line Balance

Sep-98

				Closest matching Line # ->	67	63	66	69	68	74	72	65	70	76	62	64	75
				Product ->	BW40, MB40	LFP40, TRM40	L44T, WGV40	CWD40, MCD40, STV3, STV44	DBW45	MBD45, TRMD45	DBW45, LFPD45, WGV3286	L55T, QT40, QTD45, WGV50	LD55T, STVD55	CWD50, DWGV50, MCD50	BW50, MB50, MC50, SMB50, TRM50	FTS12N, FTS12Y, QT50	LFP10N, LFP10V, PSS10N, PSS10V, TRMS10N, TRMS10V
60	Minutes			Number of Die Changes ->													
20	Minutes			Number of Profile Changes ->	1			1			1	1		1		1	
5	Minutes			Number of Color Changes ->	22	16	26	50	8	20	22	58	28	34	59	48	72
				Total Minutes for Changeovers ->	130	80	130	270	40	100	130	310	140	190	245	260	360
				Mfg. Leadtime (mL) ->	1	1	1	1	1	1	1	1	1	1	1	1	1
				Required Minutes/Day ->	1102	1440	1530	1460	1124	1365	1328	615	1122	1182	982	1362	1363
				Available Capacity (Minutes/Day) ->	1310	1360	1310	1170	1400	1340	1310	1130	1300	1250	1195	1180	1090
				Required Ctns/Day ->	278	315	343	334	305	328	300	140	256	233	252	413	341
				Available Capacity (Ctns/Day) ->	330	298	294	267	381	320	296	257	297	299	308	358	271
			Avg. Daily Demand	Avg. Min/Day													
A	BW0P05	10.0	40.4	115.1													
P	BW40	10.0	159.3	618.8	1.00												
P	BW50	11.0	63.6	239.3											1.00		
P	CWD40	12.0	58.7	255.5				1.00									
P	CWD50	12.0	16.1	65.4										1.00			
P	DBW45	10.0	381.8	1404.4					0.80		0.20						
P	DWGV50	12.0	184.1	706.6										1.00			
P	L44T	14.0	62.0	274.9			1.00										
P	L55T	14.0	35.6	156.3								1.00					

The numbered items below correspond to the circled numbers in the snapshot of Line Balance above.

(1) This column contains the names of the 58 product families. Each family had an average of 11 colors for a total of 643 products. The column to the right of the family name column contains the number of colors in each family. The next column to the right has the Average Daily Demand (cartons/day) for each of the families, and the next column has the Avg. Daily Demand that has been converted to Average Minutes/Day.

(2) The body of Line Balance is a "binary" matrix used to turn the products on or off for a given line. (It is not a true binary matrix since portions of a product can be assigned to different lines. The product DBW45 shows an 80/20 split between two lines.) The columns of the matrix represented the 16 extrusion lines. For example: Line 67 (the first Extrusion line column shows that two products are scheduled to be made on that line, BW40 and MB40.) A quick look at the binary part of the matrix show that a "1" has been placed in the cell that corresponds to both product row BW40 and line column 67.

(3) This section shows which products have been "turned on" in the matrix below. The names appear automatically whenever a value greater than zero is put into the matrix.

(4) Section (4) tracks the time lost to changeovers. The number of die changes and profile changes must be entered by hand, but the color changes are calculated automatically.

(5) This section is for the time values for each of the changeover operations.

(6) The Required Minutes/Day accumulates the Average Minutes/Day for each of the products that have been assigned to the line. The Available capacity is equal to the 1440 minutes/day in a 24 hour work day, minus the amount of time lost to changeovers.

(7) Section (7) re-converts the Required and Available minutes/day into Required and Available cartons/day. This information is more intuitive to plant personnel is a fairly accurate measure of capacity for use in the spreadsheet models.

(8) This is a drop-down box that allows the user to quickly pick the month's data to be used in the spreadsheet. The raw data was in a separate sheet.

This page intentionally left blank.

Appendix B - Derivation of Maximum "n"

The derivation of value of n at the maximum buffer quantity.

Equation (7.1)

$$B = n\mu + Z\sigma\sqrt{n} - Cn$$

Take the first derivative with respect to n,
and set the equation equal to zero.

$$\frac{dB}{dn} = \mu + \frac{Z\sigma}{2\sqrt{n}} - C = 0$$

Solve for n.

$$\frac{Z\sigma}{2\sqrt{n}} = C - \mu$$

$$\frac{2\sqrt{n}}{Z\sigma} = \frac{1}{C - \mu}$$

$$\sqrt{n} = \frac{Z\sigma}{2(C - \mu)}$$

$$n = \left(\frac{Z\sigma}{2(C - \mu)}\right)^2$$

This page intentionally left blank.

Appendix C - Base Stock Spreadsheet

A snapshot of the Base Stock Model spreadsheet tool, used for determining stores and buffers for individual extrusion lines and there associated products.

This spreadsheet is used for calculating STORE and BUFFER inventories using a Base Stock model
The raw data can be found in the 'Inv. Calc. Data.xls' workbook.

(1) Input the following 4 values:

Stores service level	98.0%	(Must be <100%)
Buffer service level	98.0%	(Must be <100%)
Lead time (days)	2.00	(Almost always 2 for our system.)
Capacity (ctns)	320.00	= 88.8% Utilization (This value comes from the Line Balance tool, or from experience.)

(2) Useful information:

Total Avg. ctns/day	284.26
Std. Dev. ctns/day	157.44
Weighted Avg. Ctns/Skid	40.00
% in Buffer (min. = 60%)	61%

(3) Results: (See below for details.)

Total Store (skids) =	40
Buffer (skids) =	19
Total (skids) =	59

Store Skids	Buffer Skids	Buffer?	Average	Std. Dev.	Ctns/Skid	Item Number	Put the raw data in the white area below					
3	-		20.2	20.2	40	WGV40 02	59	-	38	41	7	14
6	6	1	53.5	41.4	40	WGV40 04	177	-	60	55	24	55
2	-		10.0	11.6	40	WGV40 10	8	-	-	-	8	-
2	-		11.7	13.1	40	WGV40 17	16	-	29	33	-	-
5	5	1	42.8	32.5	40	WGV40 22	68	12	58	33	5	53
2	-		13.4	13.6	40	WGV40 30	39	-	3	25	4	18
3	-		16.6	16.8	40	WGV40 31	43	-	9	13	-	30
2	-		12.3	14.6	40	WGV40 35	10	-	10	-	6	-
4	3	1	25.7	24.4	40	WGV40 36	34	9	24	56	11	12
3	-		17.5	17.0	40	WGV40 39	20	16	24	8	15	-
6	6	1	52.0	41.7	40	WGV40 52	142	24	24	33	4	7
2	-		8.5	11.0	40	WGV40 68	20	-	8	39	12	5
-	-		-	-								

This page intentionally left blank.

Appendix D - Derivation of Maximum "B"

The derivation of the maximum buffer quantity. (B)

Start with Equation (7.1)

$$Max.Demand = n\mu + Z\sigma\sqrt{n} - Cn$$

and Equation (7.2)

$$n = \left(\frac{Z\sigma}{2(C-\mu)}\right)^2$$

Substitute Equation (7.2) into (7.1)

$$MaxB = \mu\left(\frac{Z\sigma}{2(C-\mu)}\right)^2 + \frac{Z^2\sigma^2}{2(C-\mu)} - C\left(\frac{Z\sigma}{2(C-\mu)}\right)^2$$

Simplify the resulting equation

$$MaxB = \frac{\mu Z^2\sigma^2}{4(C-\mu)^2} + \frac{Z^2\sigma^2}{2(C-\mu)} - \frac{CZ^2\sigma^2}{4(C-\mu)^2}$$

$$MaxB = \frac{\mu Z^2\sigma^2 + Z^2\sigma^2 2(C-\mu) - CZ^2\sigma^2}{4(C-\mu)^2}$$

$$MaxB = \frac{Z^2\sigma^2(\mu + 2C - 2\mu - C)}{4(C-\mu)^2}$$

$$MaxB = \frac{Z^2\sigma^2(C-\mu)}{4(C-\mu)^2}$$

$$MaxB = \frac{Z^2\sigma^2}{4(C-\mu)}$$

Note: This = n(C - μ) at the optimal value of n

THESIS PROCESSING SLIP

FIXED FIELD: ill. ______ name ______

index ______ biblio ______

▸ COPIES: Archives Aero Dewey Eng Hum

Lindgren Music Rotch Science

TITLE VARIES: ▸☐ ______

NAME VARIES: ▸☐ ______

IMPRINT: (COPYRIGHT) ______

▸ COLLATION: 69 p

▸ ADD: DEGREE: S.M. ▸ DEPT.: M.E.

SUPERVISORS: ______

NOTES:

cat'r: date:

page: J139,211

▸ DEPT: Mgt

▸ YEAR: 1999 ▸ DEGREE: S.M.

▸ NAME: MILBY, Michael ~~Gary~~

Gary